



# **Environmental Water Program: Restoring Ecosystem Processes Through Geomorphic High Flow Prescriptions**

**FINAL DRAFT**

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## Table of Contents

<b>1</b>	<b>PROJECT PURPOSE .....</b>	<b>1</b>
1.1	Background .....	1
1.2	Document Structure .....	1
<b>2</b>	<b>REVIEW OF HIGH FLOW PRESCRIPTION PROGRAMS .....</b>	<b>2</b>
2.1	Environmental Water Acquisition Initiatives in the Central Valley .....	2
2.1.1	<i>CVPIA Water programs .....</i>	<i>2</i>
2.1.2	<i>CALFED water programs .....</i>	<i>3</i>
2.2	Planning Processes to Guide Environmental Water Acquisition and Application .....	3
2.2.1	<i>WAP prioritization process .....</i>	<i>4</i>
2.2.2	<i>North of Delta Offstream Storage Program and the Flow Regime Technical Advisory Group .....</i>	<i>4</i>
2.2.3	<i>CALFED ERP Independent Science Board's adaptive management workshop .....</i>	<i>5</i>
2.3	Other Flow Release Investigations .....	6
2.3.1	<i>Review of program origins and objectives .....</i>	<i>7</i>
2.3.2	<i>Review of high flow goals, objectives and definitions .....</i>	<i>8</i>
2.3.3	<i>Review of program results and conclusions .....</i>	<i>10</i>
<b>3</b>	<b>PRESCRIBING GEOMORPHIC HIGH FLOWS BY ECOSYSTEM FUNCTION</b>	<b>13</b>
3.1	Introduction .....	13
3.2	Framework for Prescribing High Flows .....	13
3.3	Step 1: Deriving the Initial Vision .....	15
3.4	Step 2: Determining Watershed Historical Disturbance Regime .....	17
3.4.1	<i>Need for watershed historical context .....</i>	<i>17</i>
3.4.2	<i>Selecting appropriate high flows .....</i>	<i>18</i>
3.5	Step 3: Defining Conceptual Models of Morphodynamic River Types in the Central Valley .....	21
3.5.1	<i>Morphodynamic channel types .....</i>	<i>21</i>
3.5.2	<i>Conceptual models of unimpaired and impaired river functioning .....</i>	<i>22</i>
3.6	Steps 4 and 5: Defining Ecosystem Objectives According to High Flow Types .....	23
3.6.1	<i>High flow classification .....</i>	<i>23</i>
3.6.2	<i>Factors not linked to high flows .....</i>	<i>25</i>
3.6.3	<i>Steps 5A-5C: Analyzing high flows by type .....</i>	<i>25</i>
3.6.3.1	<i>Depth maintenance flows .....</i>	<i>25</i>
3.6.3.2	<i>Channel bed maintenance flows .....</i>	<i>25</i>
3.6.3.3	<i>Channel morphology maintenance flows .....</i>	<i>25</i>
3.6.3.4	<i>Floodplain maintenance flows .....</i>	<i>25</i>
3.7	Analytical Models: Summary of State-of-the-Science .....	25
3.7.1	<i>One-dimensional hydraulic analysis .....</i>	<i>25</i>
3.7.2	<i>Two- and three-dimensional analyses .....</i>	<i>25</i>
3.7.3	<i>Instream habitat analysis .....</i>	<i>25</i>
3.7.4	<i>Sediment transport analysis .....</i>	<i>25</i>
3.7.5	<i>Sediment dispersion analysis .....</i>	<i>25</i>
3.7.6	<i>Bank stability analysis .....</i>	<i>25</i>
3.7.7	<i>Meander migration analysis .....</i>	<i>25</i>
3.8	Field Methods: Techniques Summary .....	25
3.8.1	<i>Aerial photographic analysis .....</i>	<i>25</i>
3.8.2	<i>Channel cross sections .....</i>	<i>25</i>
3.8.3	<i>Topographic survey of bars .....</i>	<i>25</i>
3.8.4	<i>Longitudinal profiles .....</i>	<i>25</i>
3.8.5	<i>Facies mapping .....</i>	<i>25</i>

3.8.6	<i>Field estimation of roughness factor</i> .....	25
3.8.7	<i>Pebble counts</i> .....	25
3.8.8	<i>Permeability</i> .....	25
3.8.9	<i>Bulk samples</i> .....	25
3.8.10	<i>Fine sediment pool filling</i> .....	25
3.8.11	<i>Scour chains</i> .....	25
3.8.12	<i>Scour cores</i> .....	25
3.8.13	<i>Tracers</i> .....	25
3.8.14	<i>Bank erosion pins</i> .....	25
3.8.15	<i>Bank strength</i> .....	25
3.8.16	<i>Floodplain sediment traps</i> .....	25
3.8.17	<i>Vegetation survey</i> .....	25
3.8.18	<i>Suspended sediment sampling</i> .....	25
3.8.19	<i>Bedload sediment sampling</i> .....	25
3.8.20	<i>Stream gauging</i> .....	25
<b>4</b>	<b>SELECTION OF THREE STREAMS FOR PILOT STUDY</b> .....	<b>25</b>
4.1	Selection Rationale .....	25
4.2	Description of Potential Pilot Streams .....	25
4.2.1	<i>Butte Creek</i> .....	25
4.2.2	<i>Clear Creek</i> .....	25
4.2.3	<i>Tuolumne River</i> .....	25
<b>5</b>	<b>DRAFT SCIENTIFIC HYPOTHESES</b> .....	<b>25</b>
5.1	Sediment Transport and Instream Habitat.....	25
5.1.1	<i>Problem statement</i> .....	25
5.1.2	<i>Summary of existing information</i> .....	25
5.1.3	<i>Overview of experiment</i> .....	25
5.1.4	<i>Hypotheses and experimental designs</i> .....	25
5.2	Salmonid Growth in Gravel-bedded Streams: In-channel vs. Floodplain.....	25
5.2.1	<i>Problem statement</i> .....	25
5.2.2	<i>Summary of existing information</i> .....	25
5.2.3	<i>Overview of experiments</i> .....	25
5.2.4	<i>Hypotheses and experimental designs</i> .....	25
<b>6</b>	<b>CONCLUSION AND PROSPECT</b> .....	<b>25</b>
<b>7</b>	<b>REFERENCES</b> .....	<b>25</b>

### List of Tables

Table 1.	Biological resource implications of the 1996 Grand Canyon controlled flood. ....	11
Table 2.	Gauging information on selected Central Valley tributaries. ....	20
Table 3.	Prescribed high flow types in relation to ecosystem objectives. ....	24
Table 4.	Analytical methods for assessing high flows. ....	25
Table 5.	Advantages and disadvantages of geomorphic-scale flow enhancements in Clear Creek and the Tuolumne River. ....	25
Table 6.	Selection criteria applied to Central Valley tributaries identified in the USFWS first tier for high flow restoration potential. ....	25

### List of Figures

- Figure 1: Primary fluvial geomorphic management objectives for the Trinity River by water-year class.
- Figure 2: Flow releases necessary to meet microhabitat, fluvial geomorphic, summer/fall temperature, and smolt temperature management objectives during a West water year.

- Figure 3: Recommended releases during an Extremely Wet water-year compared to unimpaired inflow to Trinity Lake for WY 1995.
- Figure 4: Recommended releases during a Wet water-year compared to unimpaired inflow into Trinity Lake for in WY 1940.
- Figure 5: Recommended release during a Normal water year compared to unimpaired inflow into Trinity Lake for WY 1943.
- Figure 6: Recommended releases during a Dry water-year compared to unimpaired inflow to Trinity Lake for WY 1930.
- Figure 7: Recommended releases during a Critically Dry water-year compared to unimpaired inflow to Trinity Lake for WY 1920.
- Figure 8: Interrelationships and stepwise connections of response variables and processes between controlling variables and Canyon resource and use status – GCES.
- Figure 9: Outline of short-term research questions for analyzing resource responses – GCES.
- Figure 10: Dendrogram of research discharges – GCES.
- Figure 11: Research discharge flow schedules for 1990 and 1991-GCES.
- Figure 12: Hydrographs showing instantaneous discharges for the 1996 controlled flood at three locations in Grand Canyon – GCCF.
- Figure 13: Adaptive management framework for high flow prescription.
- Figure 14: Tuolumne River annual hydrographs of inflow to New Don Pedro Reservoir (unregulated) and flow at La Grange (regulated) for a normal water year (1971).
- Figure 15: Tuolumne River annual maximum flood frequency curves for unimpaired and post-New Don Pedro Project periods at La Grange.
- Figure 16: Sand bed (unconfined) reference condition conceptual model.
- Figure 17: Gravel bed (unconfined) reference condition conceptual model.
- Figure 18: Gravel bed (confined by bedrock banks, limited floodplain) reference condition conceptual model.
- Figure 19: Gravel bed (unconfined) disturbed by dam conceptual model.
- Figure 20: Gravel bed (unconfined) disturbed by dam and protected by levees conceptual model.
- Figure 21: Gravel bed (unconfined) disturbed by dam and in-stream mining conceptual model.
- Figure 22: Gravel bed (unconfined) disturbed by dam with managed peak flows and gravel augmentation conceptual model.
- Figure 23: Two aerial photographs of Knight's Ferry on the Stanislaus River.
- Figure 24: Pre- and post-1997 high flow cross sections showing channel down cutting on the Tuolumne River at Old La Grange Bridge (RM 50.5).
- Figure 25: Example of a site map showing cross section locations and references to benchmarks from permanent features.
- Figure 26: Simplified longitudinal profile showing morphological units and the water surface elevations at different discharges.
- Figure 27: Facies map of bed material in the East Fork River in Wyoming.
- Figure 28: A reach of the Merced River, near Yosemite, California with a calculated Manning's  $n$  value of 0.065.
- Figure 29: Cowan's (1956) table of primary factors to estimate the Manning's  $n$  roughness coefficient.
- Figure 30: Axes used to assess sediment size.
- Figure 31: Equipment necessary to measure permeability.
- Figure 32: Modified McNeil sampler with excavated material in the reservoir.
- Figure 33: CO<sub>2</sub> freeze core probe.
- Figure 34: Measurement of the depth of fines in a residual pool to calculate  $V^*$ .
- Figure 35: Scour chains before and after scour and after scour and fill.
- Figure 36: Movement of tracers through sediment.
- Figure 37: Application of bank erosion pins to quantify bank erosion.

- Figure 38: Diagram of vegetation transect locations and the resulting species composition table.  
Figure 39: US DH-48 suspended sediment sampler.  
Figure 40: Helley-Smith pressure difference bedload sampler.

# 1 PROJECT PURPOSE

The purpose of this report is to (1) assist CALFED and CALFED agency staff in the continuing development of the Ecosystem Restoration Program's (ERP) Environmental Water Program acquisition framework and pilot water acquisition program by identifying the flows needed to maintain or restore ecological functions, and (2) assist with the water acquisition aspects of the 2003 draft Stage 1 Implementation Plan. This document focuses in particular on the role of high flows in restoring the geomorphic purposes that assist in ecosystem restoration.

## 1.1 Background

The goal of the CALFED Environmental Water Program (EWP) is to acquire water from willing sellers to dedicate to environmental purposes. An important first step in developing the EWP includes defining where, and under what conditions, additional flows will be needed to achieve ecological and biological objectives. The U.S. Fish and Wildlife Service (USFWS) has been developing a Water Acquisition Program prioritization process to help identify and prioritize environmental water needs to meet biological objectives. To support the development of the EWP, and to complement the USFWS Water Acquisition Program prioritization process, CALFED has solicited environmental consulting services to help define ecosystem flow needs in Bay-Delta tributaries, focusing primarily upon identifying flow requirements for restoring fluvial geomorphic processes. Because of the importance of the EWP, and the value of water for its multiple uses, we are proposing a step-wise, three-phase process to help identify ecosystem flow needs. The first phase involves a peer-reviewed scoping investigation of the role of "geomorphic" high flows in ecosystem restoration; the second phase involves the pilot application of the peer-reviewed methods to a set of demonstration streams; and the third phase involves refining the methods and applying them to key Central Valley tributaries. This document encompasses activities related to the first phase peer-reviewed scoping process. This document is intentionally generic and does not address the process of choosing specific restoration objectives in particular instances; instead, it provides the framework for geomorphic analysis of a range of prospective high-flow driven ecosystem objectives.

## 1.2 Document Structure

This document incorporates four major components. First (Chapter 2), it places this project within the context of related projects, including several other water acquisition initiatives in the Central Valley and three other high flow prescription projects in the western United States that potentially contain useful guidance for the current project. Second (Chapter 3), a method is derived for prescribing high flow experiments according to their geomorphic function. Ten high flow types are defined and a framework is formulated for analyzing prescription requirements. Analysis is based on conceptual models, representing different stream types under unimpaired and impaired conditions, and computer models and field monitoring methods used to simulate the impact of proposed high flows and later to monitor and evaluate their actual impact. Chapter 3 includes a characterization of typical flow regimes in the Central Valley as a basis for understanding the potential for high flow prescription. The third component (Chapter 4) involves the selection of three streams that appear to be highly suitable for pilot high flow prescription experiments. The fourth component (Chapter 5) develops example draft scientific hypotheses suitable for investigation under the EWP pilot program (i.e., experiments that might utilize the high flow prescription methods developed in this document). The document concludes with a prospect in Chapter 6.

## 2 REVIEW OF HIGH FLOW PRESCRIPTION PROGRAMS

### 2.1 Environmental Water Acquisition Initiatives in the Central Valley

The two largest ecosystem restoration and resource management efforts active in the Central Valley—CALFED and the Central Valley Project Improvement Act (CVPIA)—have both developed programs for acquiring water for dedication to environmental needs. This section briefly describes the CALFED and CVPIA programs that have been developed to acquire, dedicate, and manage water for environmental application. This background provides context for understanding the role of CALFED’s EWP, for which this report has been commissioned.

#### 2.1.1 CVPIA Water programs

The CVPIA (Public Law 102-575) was enacted in 1992 to reduce the effects of the Central Valley Project (CVP) upon fish and wildlife populations in the Bay-Delta ecosystem. As the central feature of California’s water supply system, the CVP has played a significant role in powering the state’s economy by providing water for millions of acres of irrigated agriculture, as well as water for municipal consumption. The development and operation of the CVP has also played a significant role in altering riverine and estuarine habitats in the Central Valley by radically altering flow regimes. The CVPIA includes several measures for restoring fish and wildlife habitats, including: improving access to historical habitat areas upstream of dams; reducing entrainment of fish in water infrastructure; enhancing habitat; and releasing water from CVP dams to improve habitat conditions. There are two key components of the CVPIA that focus on dedicating, acquiring, and managing water of the benefit of the Bay-Delta ecosystem—(b)(2) and (b)(3) water.

##### CVPIA (b)(2) water

Section 3406(b)(2) of the CVPIA reserves 800,000 acre-feet (AF) of annual CVP yield for dedication to fish, wildlife, and habitat restoration needs. This water is often referred to as (b)(2) water, in reference to the section of the CVPIA that authorizes this dedication of water. The program to manage (b)(2) water functions much like a bank account, with a finite amount of water stored in CVP reservoirs available for environmental application every year. Federal resource managers, in collaboration with state agencies, make “withdrawals” of (b)(2) water from CVP dams through flow releases, which are targeted to satisfy environmental needs. Each withdrawal reduces the amount of stored water available for other environmental flow releases in that year. Consequently, resource managers must balance competing environmental needs for water in the Central Valley, making difficult decisions about where to release water, and how much to release, in a manner that meets immediate environmental needs but reserves enough (b)(2) water to satisfy environmental flow needs later in the year. Unlike the CVPIA (b)(3) and CALFED EWP programs, (b)(2) water is not acquired from willing sellers; rather, it is reserved every year as a portion of annual CVP yield.

##### CVPIA (b)(3) water: the Water Acquisition Program

Section 3406(b)(3) of the CVPIA authorizes the purchase of water, in addition to the annual dedication of (b)(2) water, to meet environmental flow needs. Because of the section of the CVPIA authorizing this water purchase program, this water is often referred to as (b)(3) water. Section (b)(3) stimulated the development of the CVPIA Water Acquisition Program (WAP), which has been active in purchasing water from willing sellers for dedication to environmental use. The (b)(3) water program is the closest analog to CALFED’s EWP, because they both involve acquiring water from willing sellers. As a result, the CVPIA WAP and CALFED EWP programs struggle with similar issues, as described below. Coordination between the two programs is improving.

### **2.1.2 CALFED water programs**

CALFED has developed two programs that involve acquiring and managing water to satisfy environmental flow needs in the Bay-Delta ecosystem. The Environmental Water Account is a water acquisition and management program applied principally in the Bay-Delta estuary. The EWP is focused primarily upon acquiring and managing water for environmental flow needs on Bay-Delta tributaries.

#### **Environmental Water Account (EWA)**

CALFED developed the EWA to provide flexibility in the operation of the south Delta pumps, which are a key flashpoint in the conflict between water supply operations and protection of sensitive fish species. High-capacity pumps located in the southern Delta lift water into the California Aqueduct (operated as part of the State Water Project) and Delta-Mendota Canal (operated as part of the CVP), which supply agricultural water needs in the San Joaquin valley and municipal water needs in southern California. Operation of these pumps is seasonally restricted when sensitive fish species (e.g., juvenile winter-run chinook salmon, Delta smelt) migrate within the zone of influence of the pumps. The general goal of the EWA is to acquire, store, exchange, and release water in a manner that allows for the curtailment of pump operations during periods of risk to sensitive fish species, balanced by periods of greater water export from the Delta when risk to sensitive fish species is lower. Much like CVPIA (b)(2) water, the EWA operates like a bank account, with a finite amount of water available to resource managers. The EWA has an annual target of approximately 400,000 AF of water assets, about half of which is acquired from willing sellers, and the other half of which is obtained by increased diversions of water during periods of low risk to sensitive fish species. The EWA differs from CVPIA (b)(2) and (b)(3) water, as well as the EWP, since it focuses primarily on the operation of the south Delta pumps in the Bay-Delta estuary.

#### **Environmental Water Program (EWP)**

Much like CVPIA's WAP, CALFED developed the EWP to acquire and manage water for dedication to environmental flow needs, principally in Bay-Delta tributaries. The EWP is a part of CALFED's ERP, which has defined a range of environmental flow needs and flow targets for Bay-Delta tributaries. CALFED estimates the EWP will be used to acquire 100,000 AF of water each year during the first seven years of implementation (CALFED 2000). Like the CVPIA WAP, CALFED's EWP must address several questions in determining how to prioritize and strategically acquire water to optimize environmental benefits. For example, both programs must determine the geographic areas where the purchase of water for environmental application will have a significant effect, as well as the quantity of water to acquire. Each program must also define the conditions in which water will be needed for environmental application, including seasonal needs or needs defined by environmental conditions (e.g., a dry year with little streamflow). The WAP and EWP will also need to determine how to acquire water (i.e., the purchase of a water right; the purchase of a dry-year option on a water right; purchasing a lease of a water right for a defined period of time; etc.).

## **2.2 Planning Processes to Guide Environmental Water Acquisition and Application**

There are several previous and parallel planning activities underway that will help guide the CVPIA and CALFED water acquisition programs. Some of these activities (e.g., the Water Acquisition Prioritization Program) are designed specifically to guide water acquisition. There are also other, more general planning activities that are not tied specifically to water acquisition, but nevertheless will help to define environmental water needs and guide the application of acquired

water. We briefly describe three planning activities that have or will inform the process of defining environmental flow needs and prioritizing those needs: the CVPIA Water Acquisition Program prioritization process; North of Delta Storage scientific investigation; and the CALFED Independent Science Board Adaptive Management Workshop.

### **2.2.1 WAP prioritization process**

To help guide the acquisition of environmental water under Section 3406(b)(3) of the CVPIA, the USFWS initiated a series of workshops involving personnel from state and federal agencies, as well as stakeholder representatives. The workshops focused on developing a clear, rational process for prioritizing Bay-Delta tributaries for water acquisition. The workshops assessed 19 tributaries of the Sacramento and San Joaquin Rivers, focusing primarily upon direct flow benefits to fish species, especially sensitive fish species. A strength of this WAP prioritization process was the methodical consideration of how flow releases on different tributaries could directly benefit fish species by: providing passage past flow-related barriers; maintaining suitable temperatures for fish; providing hydraulic conditions to facilitate spawning; and providing emigration pulses for juvenile salmonids. Though the WAP prioritization process successfully evaluated and compared the direct linkages between flow and fish needs, one limitation of the process was the cursory evaluation of environmental flow needs for restoring fluvial geomorphic processes, which are also important for creating and maintaining suitable habitat conditions for fish and other species. CALFED has adopted an ecosystem-based approach to restoring the Bay-Delta ecosystem, which emphasizes restoring fundamental ecological processes and the building blocks of habitat (e.g., sediment, large woody debris) as a means of creating and maintaining habitats for a multitude of species. Consequently, it is also important to consider the flows required to restore fluvial geomorphic processes. This report focuses upon linkages between flow and fluvial geomorphic processes and, as such, serves as a complement to the initial WAP prioritization results.

### **2.2.2 North of Delta Offstream Storage Program and the Flow Regime Technical Advisory Group**

During its planning phase, CALFED integrated a number of storage investigations, being conducted by CALFED and constituent CALFED agencies, into the Integrated Storage Investigation (ISI). One such investigation includes Sites Reservoir, a potential off-stream storage project on the Sacramento River now known as the North of Delta Offstream Storage (NoDOS) program. While scoping the potential operation of Sites Reservoir, it was assumed that flows between 5,000 to 10,000 cfs would be diverted from the mainstem Sacramento River as a means of filling the reservoir. To assist the evaluation of the potential Sites Reservoir project, the CALFED ISI initiated a study of environmental flow needs for riparian vegetation recruitment on the mainstem Sacramento River (CH2MHill 2000). The purpose of the study was to understand the potential impacts of diverting the 5,000 to 10,000 cubic feet per second of flow from the Sacramento River upon its riparian habitat. The study examined many of the linkages between flow and the recruitment and establishment of woody riparian vegetation. The study also examined linkages between flow and fluvial geomorphic processes (e.g., meander migration modeling), because they exert considerable influence on riparian vegetation recruitment and establishment. Consequently, the ISI investigation of flow needs on the Sacramento River can serve as a useful complement to the results of the WAP prioritization process, which focused primarily upon flow-biology linkages. One limitation of the ISI investigation's utility to the WAP and EWP programs is its focus on the mainstem Sacramento River, which differs from the tributary focus of the WAP and EWP. Some of the insights and suggestions contained in the ISI report can be generalized to inform the WAP and EWP deliberations on tributary streams, but the

difference in scale between the Sacramento River and its tributaries may limit the application of its findings.

Several environmental studies are planned as part of the NoDOS program, including investigations focused on the linkages between the flow regime and fluvial geomorphic processes on the mainstem Sacramento River. These environmental flow studies will address many of the same questions that need to be answered to guide the WAP and EWP programs in tributary streams, and coordination can produce valuable opportunities for addressing key uncertainties at different spatial scales. The NoDOS program has convened a Flow Regime Technical Advisory Group (TAG) to assist the process of designing investigations about the flow regime on the mainstem Sacramento River. Initial meetings of the Flow Regime TAG have focused on developing a mission statement and objectives. The contents of this report (developed for the EWP) address questions that the Flow Regime TAG will likely encounter in later meetings. This report can be used to help build coordination between the EWP and the TAG.

### **2.2.3 CALFED ERP Independent Science Board's adaptive management workshop**

The CALFED ERP Independent Science Board convened a workshop on March 19–20, 2002 to identify, discuss, and structure potential large-scale adaptive management actions for CALFED to pursue. The workshop featured three separate forums arranged by topic, and one forum focused on the manipulation of flow in rivers and streams for the purposes of restoration. Much of the discussion focused on the role of high flows in creating and maintaining aquatic and riparian habitats.

The workshop discussion emphasized the potential of geomorphic flows for:

- Reactivating natural geomorphic processes;
- Increasing habitat complexity;
- Restoring some riparian vegetation;
- Increasing spawning success and early survival of salmonids; and
- Increasing abundance of other native species.

One product of the workshop forum was a list of 19 questions related to geomorphic high flows, each of which requires scientific investigation. The following questions can be used as kernels for developing flow related experiments.

#### **Geomorphology:**

1. How does high flow and gravel influx influence particle size distribution?
2. How does high flow influence the interaction of gravel with woody debris?
3. To what extent does that result in habitat complexity?
4. What flow patterns mobilize fine and coarse sediments?
5. What flow is needed for channel migration and avulsion?
6. What flow inundates floodplains?
7. Do high, uncontrollable flood flows reverse the benefits achieved under controlled high flow experimentation?

#### **Riparian vegetation:**

8. What temporal pattern of flow promotes riparian forests?
9. What flow scours riparian vegetation?

**Spawning and incubation of salmonids:**

10. What flow is needed during upstream migration to minimize straying?
11. How do flow, temperature, and gravel distribution interact to influence spawning habitat?
12. What flow patterns allow for high survival of embryos?

**Rearing of salmonids:**

13. What habitat configurations maximize food supply?
14. What configurations maximize carrying capacity, growth, or survival?
15. What is the effect of varying over-wintering flow on steelhead?

**Migration of salmonids:**

16. What conditions of flow, temperature, turbidity, and maturity influence early out-migration?
17. What is the contribution of early migrants to salmonid populations?
18. Can predation by resident black bass be reduced through flow manipulation?
19. What is the effect on migration of fine-sediment loads?

Each of these questions can spawn a multitude of potential flow experiments, and workshop participants raised a set of practical questions that are useful to consider when designing flow-related experiments:

- whether it is better apply high flows in large streams that may bring great benefit, or in small streams where applications may be more practicable;
- whether it is better to release large volumes of flow in the hope of achieving multiple objectives effectively or to prescribe smaller flow releases in which experimental cause and effect may be more easily understood;
- whether geomorphic high flows can harm fisheries;
- whether it preferable to use prescribed high flows to create semi-controlled conditions (active adaptive management) or to wait for naturally occurring extreme events (passive adaptive management);
- whether flow experiments on a given stream can be replicated, and whether this limits the scientific value and transferability of insights gained from a flow experiment; and
- whether a large, uncontrolled flood event may conflict with experiments that rely upon a series of prescribed flows.

A subset of participants in the Adaptive Management Workshop is in the process of defining flow-related experiments for some of the key questions defined above (Frank Ligon [Stillwater Sciences], Scott McBain [McBain & Trush], and Wim Kimmerer [ERP Science Board]). As these experiments are drafted and refined, they can be circulated to groups like the NoDOS Flow Regime TAG to help facilitate coordination among the various planning activities related to flow releases and water acquisition.

## **2.3 Other Flow Release Investigations**

There are a number of previous and planned flow-related investigations that have been, and will be, applied on rivers in the western United States. These investigations can contribute to the process of defining flow needs and developing flow experiments on Central Valley tributaries, especially since several of these programs have been, or will be, in a position to implement flow release experiments before CALFED. We reviewed documentation for three of these flow release investigations to identify lessons useful for the EWP and WAP planning process. We examined the Trinity River Flow Evaluation (TRFE) (McBain and Trush 1997; USFWS and Hoopa Valley

Tribe 1999); the Glen Canyon Environmental Studies (GCES) (NRC 1991); and the Grand Canyon Controlled Flood (GCCF) (Webb et al. 1999).

### **2.3.1 Review of program origins and objectives**

The origins and objectives of each program differ from EWP, but all investigate the prospect of altering flow management regimes to provide multiple ecosystem benefits. The TRFE study plan is probably the closest to the EWP in terms of objectives and also in terms of morphodynamic stream type. The TRFE was initiated by a ruling by the Secretary of the Interior in 1981 that studies be conducted to determine how best to restore fishery resources of the Trinity River. The 1981 Secretarial Decision was in response to a need to fulfill a 1955 Act of Congress which, in granting construction of the Trinity River Diversion, stated also that appropriate measures be taken to preserve and propagate fish and wildlife. When diversion operations began in 1963, 88 percent of the average annual flow yield was diverted at Lewiston, California, causing significant and obvious biological and geomorphic impacts. The 1981 Secretarial Decision proposed several minimum acceptable flows as the basis for investigation, but directed also that the TRFE look at a variety of measures, including alternative flows scenarios and other management measures (USFWS and Hoopa Valley Tribe 1999). The TRFE Final Report concludes with a series of flow recommendations reported later in this document.

The GCES and GCCF studies occur on a markedly different morphodynamic stream types than occur in the Sacramento Valley (the focus of this project), and consequently have different ecosystem objectives than might be expected in studies of Sacramento Valley tributary streams. The studies began in response to the requirement for environmental assessment when the U.S. Bureau of Reclamation (USBR) was upgrading its electrical generators at Glen Canyon Dam, and were directed at a broad range of ecological and recreational issues (Wegner 1991). The Glen Canyon Dam was completed in 1963 and resulted in the almost complete loss of high flow events, reducing the two-year flow magnitude by a factor of 2.5, and providing sediment-free water with large diurnal fluctuations (Webb et al. 1999). The first phase of the GCES studies (GCESI 1982-1987) resulted in new information and some central findings, including that (Patten 1991):

- some aspects of operation of GCD have substantial adverse effects on downstream environmental and recreational resources;
- unintentional flood flow releases (about once every 4 years) damage beaches and terrestrial resources;
- fluctuating releases primarily affect recreation and aquatic resources; and
- modified operations could protect or enhance most resources.

The original study, however, was deemed to be rather inadequate partly because its study objectives were too broad and the scientific underpinning insufficiently creative, but also because of abnormally high flows during 1983-1986 that may have masked true data trends. A second phase of research was initiated to counter these inadequacies (GCESII) and within the proposed investigations, a suite of studies concerned with the interaction of high flow and sediment transport were proposed. As a basis for the identified experiments, a series of variable high flow schedules were proposed for 1990 and 1991 (Patten 1991).

Between the publication of the original conclusions of the GCESI studies and the production of the Final Environmental Impact Statement (EIS) in March 1995, there was a change in opinion about the role of floods in the system from potentially damaging to potentially beneficial, especially with regard to the transport of sand to create beach habitat (Schmidt et al. 1999). This culminated in calls for a Grand Canyon controlled flood experiment. After wide agency and

stakeholder consultation, and resolution of legal issues related to dam operation protocols and economic issues regarding the research program budget, a controlled flood flow of  $1,274 \text{ m}^3\text{s}^{-1}$  (44,900 cfs) was released over a seven-day period in March–April 1996.

### **2.3.2 Review of high flow goals, objectives and definitions**

#### **Trinity River Flow Evaluation**

The TRFE proposed high flow prescription was based on a series of investigations designed to understand functioning of the river prior to construction of the diversion, the impact of the diversion, and the current status of various key environmental factors, including (USFWS and Hoopa Valley Tribe 1999, Chapter 5):

- microhabitat,
- physical habitat of bank rehabilitation projects,
- fine sediment transport and spawning gravel flushing,
- fluvial geomorphology,
- flow variability,
- channel bed hydraulics,
- bedload budgets,
- riparian plant communities,
- flow-temperature relations, and
- chinook salmon potential production.

On the basis of this understanding, the adequacy of the flow release volumes proposed by the 1981 Secretarial Decision was assessed. It was concluded that none of the intended schedules would meet the requirements for fish, as (USFWS and Hoopa Valley Tribe 1999, Chapter 6):

- channel processes would not reach critical thresholds;
- riparian vegetation would further encroach on the channel;
- minimal flushing releases would further reduce already unsuitable spring flows;
- habitat degradation and sedimentation would continue; and
- overall fish production potential would not be realized.

As an alternative, a strategy was devised based on five components, namely that:

- a minimum of a doubling in smolt production is desirable;
- carrying capacity for fry and juveniles cannot be substantially increased within the confined riparian berms (i.e., there is insufficient flow available to scour channel margins);
- several habitat types are rare, especially low-velocity marginal habitats;
- flow releases are insufficient to provide the required smolt increases; and
- a combination of mechanical reconstruction, managed releases, and sediment management is required to achieve the objectives.

The final component arises because it is understood that high flow releases alone would be an insufficient basis for achieving the restoration objectives and, instead, a program of actions are required based on:

- high flow prescriptions;
- mechanical channel modifications designed according to the location and issues faced by individual reaches; and
- long-term sediment management including measures to prevent excess fine sediment supply and to augment coarse sediment supply.

Channel modifications are required because of the likely inability that the flow release program would be permitted to release flows of sufficient magnitude to achieve all of the strategic objectives. Anticipated actions include bank rehabilitation on forced meander bends, alternate bar rehabilitation over longer reaches, side channel reconstruction over short reaches and local removal of coarse sediment that causes backwater effects around tributary deltas. Sediment management is required because high flow prescriptions in regulated rivers cannot sufficiently restore natural rates of sediment transport. Actions in this category may include coarse sediment augmentation to restore lost gravels, annual augmentation of coarse sediment to balance the coarse sediment budget, reduction of in-stream fine sediment using sedimentation ponds and mechanical reduction of fine sediment in pools via dredging.

The TRFE also concludes that, as no single flow regime can satisfy all of the restoration objectives, a variety of high flow prescriptions are required, and should be designed to:

- match the water year type based on the annual runoff-duration curve for unregulated flows above Trinity Lake (Figure 1);
- restore the snowmelt hydrograph to which the life-history of many flora and fauna depend;
- rejuvenate and maintain alluvial processes, by water year type, including factors such as large woody debris recruitment and a recession limb to assure the sustained flows required for deposition of fine sediments on channel margin benches and seedling recruitment;
- satisfy all life stages of salmonid populations, including baseflow release for salmon spawning and rearing related to microhabitat via PHABSIM modeling and attractor flows suitable for outmigration; and
- meet salmonid temperature requirements, sub-divided by season.

The components for each flow objective, by water-year class, are described graphically via a partial hydrograph of suitable flow values (Figure 2). These partial hydrographs are overlaid to provide five annual hydrographs, one for each water year type (extremely wet, wet, normal, dry and extremely dry: Figures 3-7). Each outflow hydrograph varies progressively downstream of Lewiston Dam because of the inflow of unregulated tributary flows. The additional flows should assist in achieving geomorphic objectives while causing flow variations that reduce spawning superimposition by shifting preferred spawning habitats.

### **Glen Canyon Environmental Studies**

The second phase of GCES studies was directed in part by the 1987 National Research Council (NRC) review of the GCESI studies. The NRC recommended a series of investigations to encompass aquatic resources, terrestrial biology, sediment and hydrology, recreation, and operations. Flow and sediment transport-related issues included a requirement to study tributary processes, to include empirical approaches and modeling in hydrological studies, to link sediment studies to hydrological and biological monitoring, and to institute geomorphic studies to supplement hydraulic studies. The GCESII program began with an integration phase to identify specific research requirements followed by a research program to:

- identify and understand controlling variables;
- identify the character of crucial habitats;
- understand the magnitude of influence of controlling variables; and
- integrate the knowledge of the controlling and response variables.

The result was a conceptual model of complex ecosystem linkages (Figure 8) that made it apparent that a program of both short and long term research objectives was required. Short-term research objectives were numerous (Figure 9).

As part of the research strategy, a series of controlled research discharges were defined based on a period of sustained high flows; two weeks was the minimum period deemed appropriate for the system to reach equilibrium with the released discharge (Figure 10). The defined research discharges were placed in a schedule appropriate to satisfy downstream water users and totaled approximately six months of controlled discharges (Figure 11).

### **Grand Canyon Controlled Flood**

The GCCF was governed by the overarching aim to “measure geomorphic and ecologic processes during flood passage and test hypotheses about the flood’s effects” (Schmidt et al. 1999, p30). Many of the objectives for the flood flow were drawn from conclusions reached in the Final EIS for the generator upgrade and, in identifying the extent of current impacts, the process is somewhat similar to the method adopted in the TRFE. The eventual objectives were to:

- remove non-native fish;
- rejuvenate backwater habitats for native fish;
- redeposit sand bars at higher elevations;
- preserve and restore camping beaches;
- reduce near-shore vegetation; and
- provide water to the upper riparian zone (i.e., pre-dam zone) (Schmidt et al. 1999, page 30).

Objectives were to be achieved without significant adverse impact on the tailwater trout fishery, endangered species, cultural resources, or regional or local economies. Setting the flow levels, however, was constrained by the unwillingness of the USBR to utilize emergency spillways on the dam, capping flow release at a potential  $1,275 \text{ m}^3\text{s}^{-1}$  (45,026 cfs). This hindered prospects for a larger, shorter duration release preferred from the perspective of sediment transport objectives. The flow, as released, consisted of four days of low flow (partly to permit aerial photography of the reach) of  $227 \text{ m}^3\text{s}^{-1}$  (8,016 cfs) followed by an 11 hour ramping to  $1,274 \text{ m}^3\text{s}^{-1}$  (44,990 cfs) which was held steady for seven days. There was a subsequent 45-hour recession and then four days of low flow at  $227 \text{ m}^3\text{s}^{-1}$  (8,016 cfs) (Figure 12). The high flow peak of  $1,274 \text{ m}^3\text{s}^{-1}$  (44,990 cfs) was calculated to inundate about 10 percent of the pre-dam riparian habitat area. Tributary inflows meant that the rate of rise was greater downstream and the rate of recession slower. Pre-flood field data was collected in February 1996 and approximately 100 scientists were involved during the flood. They encountered some monitoring problems early in the experiment due to the flushing of large woody debris.

### **2.3.3 Review of program results and conclusions**

Proof of the effectiveness of high flow prescriptions can be ascertained only following their release, and issues exist regarding the transferability of high flow experiments for which there is currently insufficient data to reach a conclusion. Of the three high flow prescriptions, the TRFE experiment has probably the clearest rationale and link between ecosystem objectives and prescribed flows. The flow releases, however, have not yet occurred and may be altered in the light of political or economic pressures. Conversely, the GCCF flow experiment appears to have much looser ties between ecosystem objectives and resulting flow, but the experiment has occurred and geomorphic and biological summary accounts prepared (Schmidt 1999, Valdez et al. 1999, respectively).

The biological implications of the GCCF are concisely summarized by Valdez et al. (1999) (Table 1). Their findings are generally that the experiment produced mildly beneficial ecological changes and no adverse impacts (with the exception of the need to manually remove the kanab ambersnail [*Oxyloma haydeni kanabensis*] from proposed areas of inundation). The flood was sufficient to bury shoreline materials, but not to scour riparian and terrestrial vegetation, or to turn

over soils or disrupt germination. New backwaters were created, and primary production and consumer biomass increased, but no particular changes in fish populations were noted and the flood was insufficient to permanently suppress non-native fish populations.

**Table 1. Biological resource implications of the 1996 Grand Canyon controlled flood.**

Resource	Responses to Flood	
	Short-term	Long-term
Algae	(–) scouring decreased biomass	(+) biomass exceeded pre-flood levels, (but possibly due to high steady flows with high water clarity)
Macroinvertebrates	(–) scouring decreased densities and biomass	(+) biomass exceeded pre-flood levels, (but possibly due to high steady flows with high water clarity)
Fish habitat	(0) backwaters were restructured	(–) reattachment bars were eroded
Native fish	(0) no detectable effect	(0) no detectable effect
Non-native fish	(–) significant decrease in some species	(0) no detectable effect
Trout	(–) juveniles were displaced downstream	(0) no detectable effect
Riparian vegetation	(–) some vegetation was buried	(0) no detectable effect
Kanab Ambersnail	(–) 10% of occupied habitat inundated	(0) no detectable effect

Notes: (0) = no detectable response, (–) = undesirable response, (+) = desirable

Valdez et al. (1999) recommended that future releases are of higher magnitude and shorter duration, but still timed for March–April. One reason for the higher magnitude release would be to further attempt to suppress non-native fish. There are some concerns, however, that, while the high flow timing replicated natural conditions, the fact that the release is of cold water may adversely affect young fish populations. The low steady flows surrounding the high flow release served only to confound interpretations of flood release and should not be repeated.

The primary geomorphic objective of the GCCF was to build beach bars and alter fan-eddy complexes (Schmidt 1999). The fan-eddy complexes are a morphological unit resulting from the discharge of tributary sediments into the regulated mainstem as debris fans, causing partial flow constriction and the consequent formation of rapids and associated backwater-eddy units downstream. Following the flood, debris fans were reworked primarily by truncation. There was widespread deposition of formerly in-channel sand at high stage locations resulting in an increase in available beach-bar area. Six months later some of the flood deposits had been scoured but most high elevation material was simply re-deposited at lower elevations. Within two weeks, backwaters formed by the flood were unsuitable as rearing habitat for native fish.

Geomorphic findings included:

- tributaries supplied less fine sediment to the mainstem than expected due to decreasing sediment concentrations in time, previous sediment budget estimates need review;
- debris fan erosion and eddy deposition took only a few days, with bank failures following;
- the reworking of fans was arrested once there was an accumulation of coarse particles at the fan toe;
- eddy areas had the greatest amount of change in sediment storage;
- large scale erosion of reattachment bars in the fan-eddy complexes occurred due to mass failure processes and the realignment of primary flow directions during the flood;
- while average conditions were of deposition, net erosion occurred in some areas;
- variability in the spatial magnitude of aggradation requires close attention to the definition of project “success”; and

- longitudinal differences in patterns of change suggest that a sand balance is required as the basis for understanding physical processes dynamics.

It was concluded that high magnitude, short-duration floods are appropriate. The short duration is sufficient to re-work eddy bar and marginal deposits and would retain sediments locally. This finding is contrasted by the longer-duration flood required to suppress non-native fish and to scour non-native vegetation.

Based on the reviewed projects, a pattern emerges indicating that the science of multi-purpose high flow prescription is in its infancy and that suitable flows will vary with the morphodynamic and climatic setting of the river, the stipulated “success criteria” (quantitative objectives), and political, economic and regulatory factors. There is a high degree of uncertainty in the outcomes of prescribed high flows. However, with regard to the Glen Canyon Environmental Studies, it is argued by Luna Leopold (1991) that:

“The use of experimental flows to observe what happens under semicontrolled conditions is one of the scientific methods most likely to add new and useful information to our store of present knowledge. But the full use of these experiments will be greatly compromised if an adequate observation program is not in place at the time that they are operative. Experimental flows will, by the nature of the problem, be limited in scope and duration. We should not expect them to be more than a very modest beginning.”

## **3 PRESCRIBING GEOMORPHIC HIGH FLOWS BY ECOSYSTEM FUNCTION**

### **3.1 Introduction**

The studies reviewed in Chapter 2 provide contextual background to the methods statements developed in this chapter. The overall goal of this chapter is to present a stepped framework suitable for prescribing and analyzing high flows designed to achieve ecosystem restoration objectives in regulated rivers. Sections in this chapter correspond to several of the major steps in the framework and are focused on the modeling and field analyses required to plan suitable high flow releases of different types. The classification of high flow ‘types’ is for convenience in providing general guidance: in reality, every high flow release example will be unique and should be tailored to the ambient and historical conditions of the individual watershed.

This chapter represents a technical overview and does not address in detail the logistical issues involved in high flow prescription. The material is written primarily for scientists familiar with the topic area but should be accessible to river managers with a background in environmental science. It should be noted that very few of the named analyses have been adequately trialed under high flow release scenarios and so there is considerable uncertainty inherent to the methods presented and their expected effects. Applications of prescribed high flows are therefore genuinely experimental in nature and the information gained and applied under adaptive management is critical in incrementally improving our understanding and methods.

The ‘state-of-the-science’ statements in this chapter (Section 3.7) have been developed using the expert knowledge of the project team combined with a select review of academic literature and peer review by a panel of expert geomorphologists. The contractual basis for the report precluded an exhaustive literature survey and, as such, the methods statements should be considered as guidance rather than as definitive accounts. The project team believes, however, that the statements made herein are a reasonable indication of the state-of-the-science and give some indication of the level of certainty inherent to planning high flow releases. Release experiments would contribute to defining more robust methods.

### **3.2 Framework for Prescribing High Flows**

Figure 13 depicts a potential framework for prioritizing, assessing, implementing, and learning from high flow prescriptions. The framework is based on adaptive management principles of learning through carefully considered experimentation and is developed largely from the Trinity River adaptive management framework (USFWS and Hoopa Valley Tribe 1999). To retain focus on the mechanics of high flow prescription, the feedback loop characterizing the process of adaptive management has been omitted (see instead Downs and Kondolf 2002) but would need to be incorporated in any practical situation. The text below introduces the steps involved; steps 1-5 are examined in more detail in the following sections.

The framework consists of 14 core steps, several of which have been broken into analytical sub-steps (Figure 13). In Step 1, the initial project vision is derived using either, or a combination of, a top-down, geomorphic baseline approach or a bottom-up, biological baseline approach (Section 3.3). Whichever starting point is chosen, the methods converge on the requirement to diagnose the historical disturbance regime of the watershed and to understand the characteristics of the unimpaired (generally pre-dam) hydrograph as a guide to prescribing suitable flows (Step 2; Section 3.4). From this knowledge, conceptual models of the pre-disturbance (reference) and

post-disturbance system operation are developed in Step 3, using empirical data to the extent possible, to elucidate the pathways from the hydrology and sediment transport character of the watershed to resultant channel forms, habitats, and biota. Conceptual models should be produced for the system in its unimpaired state prior to significant human disturbance, and in its current, impaired state following anthropogenic disturbances (Section 3.5). It is likely that less river-specific data will be available for the historically unimpaired system, requiring the use of scientifically transferable data from neighboring or other similar watersheds.

The difference between the unimpaired and current system conceptual models provides the basis for determining the desirable geomorphic attributes and developing specific ecosystem objectives for the project either in terms of desirable reach attributes or factors limiting the biota (Step 4). Reach attributes or biota of concern can be referenced to the most appropriate type or types of required high flow (Step 5; Section 3.6). An integral part of identifying the key high flow ecosystem objectives is to develop a conceptual model of the desired post-rehabilitation attributes of the river that is later revised in Step 8. This model represents the most likely system response following achievement of the targeted ecosystem objectives and stands as the key reference point both for determining the success of the project and for gauging the increased understanding using an adaptive management framework (cf. Downs and Kondolf 2002). The model is based upon *a priori* knowledge of the river and its morphodynamic type(s). The post-rehabilitation conceptual model should also depict an understanding that the high flow prescription will not entirely reverse the legacy of disturbances in the watershed (i.e., full functional restoration may not be possible while there are human needs to be accommodated), so the hypothesized end condition is likely to be somewhere between the historically unimpaired and current impaired models. Hence the role of system understanding is critical in planning and later appraising the success of the high flow prescription. In identifying the key high flow system objectives, it is probable that high flows will, by themselves, be an insufficient measure and that supplementary management initiatives will be required (Section 3.6)

Analyses are required to translate the desired high flow objectives into tangible hypotheses for the effects of the high flow prescription (i.e., to progress from Step 5 to Step 6 in Figure 13). To communicate a wide variety of high flow prospects efficiently, we have classified high flows into ten high flow types (Section 3.6). The appropriate high flow type for a desired objective should be linked to its key metric (e.g., gravel mobilization) and to analytical methods necessary to determine the required flow for the desired ecosystem objective (Step 5A). In this regard, there is a basic differentiation between ‘depth-maintaining’ flow types that need only hydraulic knowledge as the basis for analysis, and the other eight flow types, aimed at maintaining the channel bed, morphology, and floodplain and that require specification of reach-level thresholds and dynamics of sediment transport. Initial analysis of each flow type will involve either computational simulation modeling of hydraulics and/or sediment transport, or field monitoring of thresholds in the performance of the key metrics. State-of-the-science summaries for the analytical methods are provided in Section 3.7. Suitable morphometric field data will be required as input to either approach (Step 5B; Section 3.8). Ideally, the simulation models will indicate the threshold condition in the key metric (e.g., the lowest flow at which a certain objective such as gravel mobilization could be achieved) and can generate an optimum combination of magnitude, frequency, and duration of flows that would achieve the flow type objective. Where possible, a sensitivity analysis using key parameters should be undertaken as an integral part of the simulation process and used to identify and quantify the level of uncertainty in the project (Step 5C). In Step 5D, the flows required to achieve individual high flow objectives are compromised within the context of the natural flow regime (determined in Step 2). It may be possible to pursue high flow objectives by water year types, using longer duration releases during wetter years when more water is available, thereby minimizing the chance of conflict with other water users.

Where multiple flow objectives are desired, the required flow magnitude and duration generated for individual objectives will need to be compared and adjusted to produce a composite hydrograph representing the best-case scenario (USFWS and Hoopa Valley Tribe 1999). Where an individual objective is compromised in selecting a practical high flow, simulation models should be re-run to ascertain if the compromised flow greatly reduces the chance of achieving the objective. This process may require a further iteration in prioritizing flow types and resolving conflicts such that the eventual “best” hydrograph may not match the original composite. Using the conceptual flow model developed in Step 5, the expected outcomes of the prescribed high flows either in physical or biotic terms can then be predicted (Step 6), noting the associated level of uncertainty in expected outcomes and the need for supplementary management actions.

Once all involved parties have agreed on a series of hydrograph prescriptions (differentiated by water year type), monitoring variables should be chosen (Step 7) to assess critical thresholds in channel behavior and the overall evaluation of the high flow releases in physical and biological terms. The monitoring variables will likely be derived from the original set of key defining parameters used in assessing the individual high flow requirements. The post-experiment conceptual model is revised again (Step 8) to reflect any management compromises prior to implementation of the project experiments (Step 9). The experiments should be monitored (Step 10) over a time period that reflects the expected time for its impacts to take effect. Where multiple experiments are prescribed, the monitoring should allow the effects of individual releases to be detected. This may involve intensive monitoring before, during, and immediately after the experiment and periodic surveys for a number of years thereafter. Monitoring should be designed to detect whether certain specified threshold conditions were reached (e.g., whether bed particles moved) and also to ascertain whether the overall dynamic of the physical parameter matched the expectations from simulation modeling (e.g., whether the total movement of bed particles met the predictions based on the magnitude-frequency simulation of high flows). It may also be necessary to extrapolate from short-term records to provide the basis for longer-term performance expectations.

The monitoring effort provides the core data for completing the adaptive management process (Steps 11–14). The data collected form the basis for both learning *about* the project (performance of prescribed high flows) in terms of system behavior and learning *from* the project regarding the adequacy of the assessment process (Step 11) (Downs and Kondolf 2002). Appraisal requires evaluation in addition to monitoring in order to conclude the experiment and restate the post-experiment conceptual model (Step 12), and also to provide input to the adaptive processes in which knowledge regarding future high flow prescriptions is adjusted and disseminated (Step 13). From the knowledge obtained, the prospect of further actions is assessed (Step 14) either by reformulating hypotheses that can clearly be rejected or, where hypotheses were accepted, by repeating the adaptive assessment process. This may involve either refined hypotheses based on re-stated conceptual models if significant change was achieved under the first set of experiments or, where the previous experiment did not achieve significant ecosystem changes, a complete revision of ecosystem goals (USFWS and Hoopa Valley Tribe 1999).

The framework described in Figure 13 represents a working model and would undoubtedly be refined in the light of practical experimentation.

### 3.3 Step 1: Deriving the Initial Vision

The interaction between high flows and ecological processes is complex and will vary according to the morphodynamic stream type in question and the ecological attributes of interest. Because

of the generally hierarchical linkage “process→form→habitat→biota”, there are two obvious starting points in trying to derive the initial vision of the project objectives (i.e., the general goals that will be later refined by the analyses outlined below). One approach is essentially top-down, beginning with watershed processes and their impact on the resultant channel forms and processes, while the other is bottom-up, beginning with the river biota and their associated habitat preferences. The watershed processes approach is considered to be a holistic indicator of ecological performance at the meso-scale, whereas the limiting factors approach is a complementary but reductionist approach focusing on identifying thresholds in the effect of stressors on target biota (Leuven and Poudevigne 2002).

The watershed processes approach is centered on restoring flow and sediment processes representative of the unimpaired (pre-disturbance) operation of the watershed. It assumes that once processes are restored by a combination of high flow events, form, habitat, and biota will eventually be restored. The starting point for a watershed processes approach is to use the historical watershed context to characterize the unimpaired and contemporary functioning of the river ecosystem. This analysis will, ideally, also indicate long-term factors (indicative of geomorphic ‘system memory’) that will influence the project outcome. Criticisms of this approach include the fact that: (1) ecosystem deficiencies related to specific factors not governed by natural flows of water and sediment (e.g., chemical factors from industrial discharges) or that occur outside of the watershed (e.g., ocean fish harvesting) may go unrecognized in the analytical process; and (2) restoring processes at a watershed level is difficult to achieve. In many rivers, particularly those regulated by dams, restrictions on high flow prescription make it unlikely that geomorphic processes can be fully restored. In practice, restoration is often targeted to achieve certain geomorphic functions and attributes, wherein the attributes provide the criteria for assessing the success of the restoration experiment. Trush et al. (2000) defined such a set of attributes for cobble and gravel-bedded alluvial rivers as part of the framework for determining Trinity River flow needs. Attributes included:

- spatially complex channel morphology;
- flow and water quality that are predictably variable;
- frequently mobilized channel bed surface;
- periodic channel bed scour and fill;
- balanced sediment budgets for both fine and coarse sediment;
- periodic channel migration;
- periodic floodplain inundation;
- infrequent channel resetting floods;
- self-sustaining riparian plant communities; and
- naturally fluctuating groundwater table.

Attribute sets require definition for each river system. They can be used to guide the implementation of individual restoration actions (e.g., the prescription of high flows) from which an associated set of habitat and biotic improvements may be expected.

The limiting factors approach is a bottom-up specification of ecosystem requirements based on the factors limiting the populations of key biota. This approach begins with the identification of species of concern and, from these, the development of biological hypotheses designed to assist in tracing current biotic impairments back through habitat and form and then to a series of physical processes (or anthropogenic disturbances) determined as the key limiting factors. In this way, the approach targets specific impairments to physical processes that, once resolved, should contribute to biological improvement. Primary criticisms of this approach include: (1) the possibility that, by focusing on the physical processes strongly associated with particular target species, physical

processes relating to the requirements of other species and with other management objectives may be overlooked; and (2) that objectives may not be attained because of unanticipated side effects arising from the attempt to modify only a few of the impaired physical processes.

In practice, the two approaches are probably most effective when used conjunctively and this is evident in the fact that the differentiation between the approaches is becoming blurred. The watershed processes approach increasingly uses species habitat requirements to focus on target attributes for the restoration strategy, while the biological limiting factors approach is moving towards a broader base of multiple sensitive and at-risk analysis species whose distribution and requirements overlap, thus reducing the prospects of incomplete analysis, unanticipated effects, and management conflicts. Both approaches were utilized for the Trinity River flow Evaluation (USFWS and Hoopa Valley Tribe 1999) and provided complementary perspectives and insights that were beyond the capability of any one approach (S. McBain, pers. comm., 2003). Irrespective of the starting point, both approaches are likely to conclude that the prescription of high flows in regulated rivers is the basic building block for creating channel forms and habitat diversity to support the achievement of biotic objectives such as improving salmonid spawning success.

### **3.4 Step 2: Determining Watershed Historical Disturbance Regime**

#### **3.4.1 Need for watershed historical context**

Analyzing the watershed historical context is a fundamental first step in river management. It provides the basis for understanding the environmental history and cultural conditioning of geomorphic system changes in time and space across the watershed. For most watersheds, this procedure equates to a cause-and-effect analysis of increasing human interventions in natural geomorphic system functioning, hence the notion of a 'disturbance regime'. The analysis is valuable in: (1) identifying the underlying causes of problems or issues leading to the need for restoration (e.g., by high flow prescription); (2) documenting historical conditions that assist in determining ecological potential; and (3) setting realistic and appropriate goals for restoration based on knowledge of desired system end states (Kondolf and Larson 1995; Kondolf and Downs 1996). The analysis is guided by four basic questions, namely (Montgomery et al. 1995):

1. How does this landscape work?
2. What has its history been?
3. What is its current condition?
4. What are the possible/desirable future states for this landscape?

Issues of landscape function are often addressed by an initial stratification of the watershed into dominant geomorphic process domains. Stratification of these domains is based on landscape-level structure and processes evident from analysis of geology, channel pattern, slope and land uses using reconnaissance surveys, analysis of aerial photographs and maps, and use of watershed models (Montgomery and Dietrich 1994; Montgomery et al. 1995; Reid and Dunne 1996; Montgomery et al. 1998). Archive data is used to reconstruct historical conditions and will be checked in the field during field surveys to assess the current condition and the legacy of past disturbances. Kondolf and Larson (1995) suggest the use of a variety of sources to determine the historical context of geomorphic system changes including flow records, repeat editions of large scale topographic maps and aerial photographs, remote sensing images, ground photographs, repeat surveys of channel cross-sections, narrative accounts, and geomorphic and vegetational field evidence. All historical analyses have associated limitations that should be recognized (see Hooke and Kain 1982; Petts 1989; Kondolf and Larson 1995; Kondolf and Piegay 2003). Increasingly, sedimentary evidence is being used in conjunction with dating techniques such as

isotopes of short-lived radioactive materials (e.g., Byrne et al. 2001), dendrochronology (Hupp 1992; Nanson et al. 1995) and macrofossil, diatom and beetle indicators (Brown 2002) to determine vertical changes in channel systems (i.e., to determine periods of incision and aggradation).

Assembling the evidence to indicate cause-and-effect system operations requires a level of detail in the analysis that is determined by the level of acceptable risk in the outcome (Montgomery et al. 1995). Assessing cause-and-effect system operations will certainly require expert interpretation as the matter cannot be adequately handled via computer models (Downs and Priestnall 2003). Practical methods for assembling the information include watershed analysis (Montgomery et al. 1995) but also cumulative impacts analysis (Reid 1993), fluvial audits (Sear et al. 1995), and sediment budgets (e.g., Reid and Dunne 1996). Whatever method is used, it will have, ideally, the following qualities (Reid 1998, page 498):

- fits the particular needs of the agency or organization instituting it;
- evaluates and potential important impacts;
- evaluates impacts at any point downstream;
- evaluates impacts accumulating through both time and space;
- evaluates the influence of any expected kind of land-use activity;
- evaluates and lands within the analysis area;
- uses the best available analysis methods for each aspect of the analysis;
- incorporates new information as understanding grows;
- can be done for a reasonable costs over a reasonable length of time;
- produces an readable and useable product; and
- is credible and widely accepted.

The realities of understanding the current channel conditions, and especially of projecting the possible future conditions, lead Reid (1998) to conclude that, at the watershed scale:

- general qualitative understanding is more important than precise numbers;
- change is more important than stasis;
- extreme conditions may be more important than averages;
- an understanding of process is more important than a description of condition; and
- the fundamental certainty is that uncertainty will remain following the analysis.

For setting restoration objectives, there is increasing interest in organizing the results of such an analysis into disturbance regimes of past human impacts at the reach scale. This organization helps establish a conceptual model of system functioning for both the unimpaired condition (i.e., a reference model of natural functions assumed to operate before intensive human activities in the watershed) and the current, impaired, system condition (see Step 3, Section 3.5).

### **3.4.2 Selecting appropriate high flows**

One major aspect of the watershed disturbance regime in the dammed tributaries of the Central Valley will involve the impact of flow regulation following dam construction and water abstraction (Figures 14 and 15). This is the basis for considering high flow prescription as a restoration activity. In setting high flows, it is probable that the magnitude, duration, frequency, and timing of prescribed flows will be based on comparison to the natural, unimpaired flows for the river. This approach is appropriate as native biota have generally evolved to be “hydraulically-optimal” under natural flow regimes. High flow prescription strategies should, therefore, be guided by an understanding of the unimpaired flow regime as part of the historical analysis. The specific attributes of the prescribed flows will later be refined in Step 5D once the

objective-led flow requirements are fully understood. Further, as river flow varies between years, it is illogical to attempt to achieve all ecosystem objectives based on high flows in every year (cf. TRFE study). Therefore, it is useful to characterize flow patterns by different water year types; for instance, by contrasting flows in extremely wet years with those in extremely dry years as a basis for ascertaining ecosystem objectives that may be achieved in each year category. As guidance in understanding characteristic flow regimes in the Central Valley, flow data were analyzed from six of the longest established gauging stations on tributaries of the Sacramento and San Joaquin rivers (Table 2). Flows obtained from online U.S. Geological Survey (USGS) databases were sub-divided into five water year classes according to frequency, encompassing Extremely Wet, Wet, Normal, Dry, and Extremely Dry year classes, with four years usually examined from the mid-range of each class group (i.e., at the 10, 30, 50, 70, and 90 percent flow exceedance, respectively).

In the Central Valley, unregulated rivers and the pre-dam records for regulated rivers typically have highest peak flows following rainfall events during the winter months, generally occurring in December–February. The winter peaks are followed by a period of above average flows and secondary peaks which are the most pronounced during wet years, especially in the Tuolumne and Feather rivers, and Clear Creek. The seasonal distribution of runoff shows a geographical pattern based on elevation and latitude wherein, to the north, Clear Creek has winter flows that are both larger and of longer duration than the spring flows under all water year types, whereas, to the south, in the Tuolumne River, spring flows provide a majority of the overall flow volume. Drier years on the Tuolumne River are characterized by a reduced magnitude of spring flow and a more pronounced reduction in the number and intensity of winter events such that the spring flows provide proportionately more of the overall flow volume. In Deer, Mill, Cottonwood, and Butte creeks, the volume of flow received through the year also varies primarily with the number and magnitude of winter peak flow events rather than with snowmelt events, such that dry years are characterized by few or no significant winter high flow events and low intervening flows.

Regulated flows on Clear Creek and the Feather and Tuolumne rivers are characterized by a dramatic reduction in the magnitude of winter peak flows, relative to the storage capacity of the impounding reservoir. On Clear Creek, total runoff volume is related to the number and magnitude of any (presumed) overtopping events resulting from large storms and to the volume of flow releases during October and November to draw down reservoir levels prior to winter. The Feather River has lost all of its high spring flows and has only remnant elements of winter flows that pass Oroville Dam. The remnant high flow events largely determine the overall flow volume received downstream. The regulated hydrograph for the Tuolumne River shows a distinct stepped pattern as flows are released according to downstream irrigation needs. During wet years, peak flows are reduced, but moderately high flows are experienced over a longer period than for the unregulated hydrographs. During dry years, peak flows and intervening flows are considerably lower.

It follows that the natural sequence of flows provides the basis against which high flow prescription protocols in the Central Valley (primarily the Sacramento Valley) will seek to achieve ecosystem objectives. Under unregulated conditions, for the larger rivers draining the High Sierra (Feather and Tuolumne) and Clear Creek to the north, there are usually two periods that might be expected to provide geomorphic flows – during individual winter storm events and during sustained spring snow melt events. Under their regulated conditions, the winter flow events are largely lost, except for Clear Creek, and the spring high flows are very much reduced. In Deer, Mill, Cottonwood, and Butte creeks, the snowmelt events are far less pronounced and may not achieve geomorphic flows objectives, leaving only manipulation of winter events to achieve high flow objectives.

**Table 2. Gauging information on selected Central Valley tributaries.**

River	Gauging Record	Peak discharge		Water Year Type (unimpaired flows)									
		Date	Discharge (cfs)	Extremely wet		Wet		Normal		Dry		Extremely dry	
				10% flow (ac-ft)	typical years	30% flow (ac-ft)	typical years	50% flow (ac-ft)	typical years	70% flow (ac-ft)	typical years	90% flow (ac-ft)	typical years
Butte Creek	1931-2000	1/1/1997	26,600	530,000	1938, 1956 1982 1988	380,000	1940 1963 1980 1993	290,000	1935 1936 1943 1943	200,000	1932 1960 1961 1972	150,000	1934 1990 1991 1994
Clear Creek Total record	1941-2000	3/1/1941	15,100	400,000	1952 1963 1964 1983	220,000	1948 1949 1959 1970	150,000	1955 1978 1993 2000	90,000	1971 1973 1975 1980	60,000	1979 1985 1987 1994
Pre-dam	1941-1962	3/1/1941	15,100	790,000	1956 1958	340,000	1953 1954	230,000	1961 1962	190,000	1945 1960	110,000	1947
With-dam	1963-2000	3/3/1983	15,000	240,000	1964 1970 1998	150,000	1978 1993 2000	87,000	1971 1973 1975	71,000	1968 1981 1992	57,000	1972 1991 1994
Cottonwood Creek	1941-2000	1/16/1974	54,300	1,200,000	1956 1974 1978 1995	770,000	1971 1975 1993 1996	570,000	1946 1951 1963 1981	350,000	1959 1979 1985 1989	190,000	1964 1987 1990 1991
Deer	1912-2000	1/1/1997	20,100	400,000	1914 1953 1958 1982	300,000	1978 1980 1984 1996	200,000	1928 1930 1936 1946	150,000	1913 1926 1959 1960	100,000	1933 1976 1988 1990
Feather Total record	1902-2000	3/19/1907	187,000	6,500,000	1906 1914 1958 1965	4,000,000	1905 1917 1936 1954	2,800,000	1925 1932 1937 1959	1,500,000	1931 1933 1982 1983	400,000	1971 1975 1988 1991
Pre-dam	1902-1967	3/19/1907	187,000	7,000,000	1906 1911 1956	5,300,000	1915 1927 1940 1943	3,700,000	1928 1930 1935 1946	2,800,000	1932 1937 1966	2,100,000	1912 1920 1929 1934
With-dam	1968-2000	2/18/1986	132,000	1,700,000	1970 1995	960,000	1969 1998	480,000	1973 1989 1992	390,000	1971 1975 1988	300,000	1979 1981
Mill Creek	1929-2000	1/1/1997	14,400	350,000	1941 1956 1958 1982	270,000	1940 1943 1980 1993	200,000	1935 1936 1945 1946	160,000	1932 1937 1966 1981	120,000	1934 1976 1991 1992
Tuolumne Total record	1918-1999	12/23/1955	118,388	2,700,000	1958 1965 1970	2,000,000	1937 1997 1998	1,300,000	1919 1920 1984	1,000,000	1929 1939 1999	170,000	1972 1973 1994
Pre-dam	1918-1970	12/23/1955	118,388	2,900,000	1965 1970 1952	2,100,000	1932 1935 1936	1,600,000	1928 1950 1962	1,300,000	1944 1949 1930	1,000,000	1929 1939 1968
With-dam	1971-1999	1/3/1997	55,865	2,000,000	1995 1997 1998	1,100,000	1986 1996 1999	380,000	1974 1976 1985	190,000	1972 1993 1994	78,000	1977 1988 1992

Consequently, the opportunity for high flow releases to achieve geomorphic ecosystem objectives is likely to be characterized by one of three prescription types, namely:

- In large regulated rivers draining the high Sierra: release of high flows during snowmelt periods, with occasional opportunities for supplementing mainstem high flows onto flows generated by unregulated tributary streams in winter storm events while still achieving flood control objectives (similar to Trinity River).
- In Clear Creek and other regulated rivers with a low storage capacity relative to annual runoff volumes: release of high flows during snowmelt periods, supplemented by fairly frequent winter high flow releases, possibly in advance of anticipated large storms.
- In creeks without significant natural spring high flows: creative use of winter high flow events prior to or following storm events.

Ultimately, high flow releases will be determined by overall management objectives that encompass riverine ecosystem requirements in conjunction with functional concerns for water resources management and flood protection. High flow releases that will meet both ecosystem and water resource management objectives are resolved later in Steps 5D and 7, but the flow prescription types characterized above give an indication of the possible options.

### **3.5 Step 3: Defining Conceptual Models of Morphodynamic River Types in the Central Valley**

For restoration purposes, watershed historical conditions and impaired regimes require organizing into an ordered set of cause-and-effect statements (conceptual models) detailing interactions in the contemporary and unimpaired systems. This information provides the basis for contemplating actions to improve current conditions. However, as the impact of various disturbances depends on the type of river under analysis, conceptual models need to be differentiated by a classification of river types.

#### **3.5.1 Morphodynamic channel types**

River systems are unique but not singular. This distinction is based on the fact that while, morphologically, river systems display an almost infinite variety of form, they are, nonetheless, governed by a series of fundamental physical processes that are common to all river systems. In typing river channels, however, preference is usually given to channel morphology (which is far easier to distinguish from field survey) over processes (e.g., Rosgen 1994, 1996). Classifying river channels is a pervasive aim because it implies some *a priori* understanding of river systems that is an important first step in organizing and conducting further investigations (Downs 1995). It provides the framework for communicating understanding about complex fluvial systems in a straightforward manner. Academic reviews of river channel classifications have drawn distinctions, for example, between channel classification (top down) and channel characterization (bottom-up) (Mosley 1987), special and general forms of classification (Kondolf 1995), morphology and process-oriented schemes (Downs 1995), and hierarchical and non-hierarchical systems (Montgomery and Buffington 1998). The basic message, however, remains throughout these studies: “No single classification can satisfy all possible purposes or is likely to encompass all possible channel types” (Montgomery and Buffington 1998, p13).

Mindful of the difficulty in achieving a rigorous solution to channel classification, the classification in this document subdivides tributaries of the Central Valley into morphodynamic categories reflective of differences in channel form, materials, and processes. The resultant channel forms are not indicative of an equilibrium form, but a given channel type is assumed to

have some central tendency in terms of morphology, habitat quality and quantity, and response to disturbance. For illustrative purposes, the resulting types are:

- sand bed river channels;
- unconfined gravel bed meandering river channels; and
- confined gravel bed river channels.

### 3.5.2 Conceptual models of unimpaired and impaired river functioning

Conceptual models of the unimpaired function for the three morphodynamic river types were developed (Figures 16–18). These are referred to as reference condition conceptual models. The difference between the reference condition model and the contemporary condition model is indicative of the impact of human disturbances in altering (usually impairing) ecosystem function. Comparison between the two models is the basis for determining the major ecosystem restoration requirements. The arrows in each model imply causal linkages from the flow and sediment inputs through to biotic response via a series of processes, forms and resultant habitat structures.

Example disturbances to river ecosystems caused by human activity in the Central Valley include:

- flow and sediment transport regulation caused by large dams and other flow diversions;
- instream gravel mining;
- mine tailings disposal;
- floodplain gravel mining and pit capture;
- floodplain aggradation as the legacy of hydraulic mining for gold;
- channel incision of rivers following cessation of gold mining and building of dams;
- dredging of navigable rivers;
- large woody debris removal;
- flood control levees;
- flood control channelization;
- bank protection works;
- urban expansion in the upper watershed;
- upslope and upstream grazing; and
- upslope and upstream de-forestation.

It is possible, therefore, to think of each morphodynamic river type responding to one or more of these disturbances, resulting in a large number of conceptual model permutations. For illustration, we have developed conceptual models for three typical disturbance regimes in unconfined gravel bed channels, namely:

- with dam operation (Figure 19);
- with dam and levees (Figure 20); and
- with dam and in-stream mining (Figure 21).

It is universally acknowledged that river restoration initiatives can rarely, if ever, restore the full pre-disturbance ecosystem in the sense defined by Cairns (1991). Recognition of this limitation is especially appropriate in the case of high flow prescriptions because, in most cases, the fundamental impairment is a large dam that remains in place even if its operational protocols are reconfigured. Therefore, a river system following prescription of high flows may be *less impaired*, but still short of its unimpaired function set. In this sense, efforts are focused on returning a system *close* to pre-disturbance conditions in terms of selected components and functions as envisaged for “restoration” by the National Research Council (1992). As an

illustration, a conceptual model (Figure 22) is developed that illustrates an unconfined gravel bed channel with a generic treatment consisting of channel bed restoring flows and gravel augmentation. It is apparent that the result (conceptually) is a channel whose functions are improved over the impaired system described in Figure 19, but still short of the reference condition in Figure 17.

### **3.6 Steps 4 and 5: Defining Ecosystem Objectives According to High Flow Types**

#### **3.6.1 High flow classification**

In considering the variety of channel attributes or the potential range of specific biotic objectives existing in natural river channels, it is apparent that there exist several characteristic high flow signatures (or types) which can be used to achieve restoration objectives. In magnitude, these flows range from elevated baseflows (i.e., “low” high flows) designed to maintain minimum water depths in certain seasons to large flood flows (i.e., “high” high flows) used to mobilize floodplain deposits. Literature regarding high flow prescription has recognized these differences and various kinds of prescribed high flows have been proposed (Reiser et al. 1989, Petts and Maddock 1994, Kondolf and Wilcock 1996, Wilcock et al. 1996), with definitions arranged by either hydrologic return period, channel morphology, or by sediment transport mechanics (Reiser et al. 1989). This document defines four classes of prescribed high flows for maintaining or restoring fluvial ecosystems. These classes include a hydrologic flow (elevated baseflow) to achieve minimum flow depth and/or velocity, and three classes of geomorphic flows designed to maintain (and potentially restore) the channel bed, channel morphology, or floodplain morphology. Within each flow class, two or three prescribed flow types can be defined, yielding a total of ten individual flow types. Table 3 relates a series of ecosystem objectives to each flow type. For brevity, Table 3 generally highlights only those ecosystem objectives that are specific to the named flow type. Because the high flow types are generally incremental as one progresses through the table, it is possible that numerous flow objectives can be achieved by prescribing one of the larger high flows. For example, release of a channel migration flow may additionally achieve the majority of the ecosystem objectives related to flows in the channel morphology maintaining and channel bed maintaining flow classes. In addition, it should be noted that the thresholds between the named flows are more for convenience in thinking about the analytical differences between flows than a real, proven distinction between types.

**Table 3. Prescribed high flow types in relation to ecosystem objectives (objectives in italics are developed as scientific hypotheses in Chapter 5).**

Primary Physical Threshold	Ecosystem Concern	Specific Ecosystem Objectives	Flow Type Required
Maintaining flow depth	Morphology	- none	'In-channel'
	Riparian habitat	- Discourage germination of riparian plants on lower bar surfaces - Cause woody riparian mortality on lower bar surfaces, promote woody riparian regeneration of upper bar surfaces previously unwetted	
	Fish habitat	- Provide suitable combinations of velocity, depth and temperature at particular times - Spatial separation of warm-water predators and salmon smolts: suppress non-native fish habitat preferences - Stimulate emigration - Attraction flows - Provide summer base flows	
	Invertebrates	- Provide suitable conditions of velocity, depth and temperature for particular life history stages to provide prey for secondary consumers	
	Morphology	- Inherently none, but if the flows are carrying suspended sediment then floodplain deposition will result (see "Floodplain Deposition Flows")	'Over-bank'
	Riparian habitat	- Maintain water table for off-channel wetlands and side channels - Promote woody riparian regeneration on floodplain	
	Fish habitat	- Rejuvenate backwater habitats for native fish - <i>Floodplain food availability</i> – for growth of juveniles - <i>Floodplain water temperatures</i> - suitable for fish use - <i>Provide floodplain habitats for utilization by rearing salmon</i> - <i>Increased juvenile salmon growth rates</i> - <i>Reduce piscine predation</i> - <i>Moderate stage change to reduce stranding</i>	
	Invertebrates	- <i>Chironomid life history</i> – provision of suitable frequency and duration of floodplain inundation	
Maintaining channel bed functions	Morphology	- Export fine sediment from pools where excess fine sediment has accumulated; essentially to create a net loss of fine sediment accumulation in the reach	'Pool scouring'
	Riparian habitat	- none	
	Fish habitat	- Maintain well-developed pools for rearing and holding	
	Invertebrates	- unknown	
	Morphology	- Remove surficial fine sediment without extensive mobilization of riffle gravel - <i>Fine sediment removal from gravels</i> - winnowing of interstitial fine sediment to maintain interstitial void space - Transport sand out of reach at volume greater than input from tributaries to reduce instream storage (where elevated fines)	'Riffle cleaning'
	Riparian habitat	- none	
	Fish habitat	- Turn riffle substrates periodically to achieve high permeability spawning habitat - Conserve stocks of limited bed material of suitable spawning size - Cause slightly elevated turbidity to reduce predation on migrating juveniles	
	Invertebrates	- Provide interstitial spaces for cover and protection of various species	

Primary Physical Threshold	Ecosystem Concern	Specific Ecosystem Objectives	Flow Type Required
	Morphology	<ul style="list-style-type: none"> <li>- <b>Bed mobilization</b> - riffle gravel mobilization, scouring channel bed greater than 1-2 multiples of D84 depth; redeposition of gravels on face of alternate bar</li> <li>- Frequent gravel mobilization to maintain interstitial void space e.g. mobilization of matrix particles (D84) on alternate bar surfaces</li> </ul>	<b>‘Riffle mobilization’</b>
	Riparian habitat	- none	
	Fish habitat	<ul style="list-style-type: none"> <li>- Mobilize riffles to ensure high permeability spawning habitat when gravel supply is ensured / augmented</li> <li>- <b>Maintain framework size gravel distribution</b></li> </ul>	
	Invertebrates	- Provide new surfaces for colonization by less armored and more available prey for benthic feeders	
<b>Maintaining channel morphology functions</b>	Morphology	<ul style="list-style-type: none"> <li>- Facilitate periodic deposition of fine sediment onto bars</li> <li>- Transport of bed material load at a rate equivalent to upstream import, facilitating alluvial deposits</li> </ul>	<b>‘Margin accretion’</b>
	Riparian habitat	<ul style="list-style-type: none"> <li>- Promote woody riparian regeneration on upper bar surfaces</li> <li>- Maintain diversity of aquatic-terrestrial transitional zone</li> </ul>	
	Fish habitat	- Provision and maintenance of shallow water, low-velocity channel edges for juvenile rearing	
	Invertebrates	- Changes in species composition caused by reduction in sand volume in substrate	
	Morphology	<ul style="list-style-type: none"> <li>- Mobilization of bed material load across full extent of unimpaired, or other pre-determined, channel width.</li> <li>- Elimination of tributary deposits in mainstem channel</li> </ul>	<b>‘Channel width’</b>
	Riparian habitat	<ul style="list-style-type: none"> <li>- Cause woody vegetation mortality on lower bar surfaces and thus prevent vegetation encroachment</li> <li>- Re-set woody vegetation community status in marginal zones</li> </ul>	
	Fish habitat	- Provision and maintenance of shallow water, low-velocity channel edges for juvenile rearing	
	Invertebrates	- unknown	
	Morphology	<ul style="list-style-type: none"> <li>- <b>Maintain channel planform</b> - sediment transport and bank erosion sufficient to cause periodic lateral migration</li> <li>- Maintenance of spatially complex channel morphology</li> </ul>	<b>‘Channel migration’</b>
	Riparian habitat	<ul style="list-style-type: none"> <li>- Create diversity and extent of river bank habitat, patch dynamics, vegetation community successions</li> <li>- Create backwater / off-stream habitat</li> </ul>	
	Fish habitat	- Provision and maintenance of shallow water, low-velocity channel edges, a existence of backwater / off-channel habitat to provide a complex mosaic of fish habitat suitable for all life stages	
	Invertebrates	- unknown	
<b>Maintaining floodplain functions</b>	Geomorphology	- Floodplain aggradation through import of fine sediment	<b>‘Floodplain deposition’</b>
	Riparian habitat	<ul style="list-style-type: none"> <li>- Provide sediment and nutrient supply to floodplain</li> <li>- Promote microtopographic variability through variable sediment deposition</li> </ul>	
	Fish habitat	<ul style="list-style-type: none"> <li>- Inundation to provide flood pulse advantage</li> <li>- Rejuvenate backwater habitats for native fish</li> </ul>	
	Invertebrates	- unknown	
	Morphology	<ul style="list-style-type: none"> <li>- Floodplain scour and fill</li> <li>- Transport of sediment onto and from floodplain</li> <li>- Channel avulsion and migration</li> </ul>	<b>‘Floodplain mobilization’</b>
	Riparian habitat	- Invoke extreme end of intermediate disturbance hypothesis: re-set floodplain ecological community status	
	Fish habitat	<ul style="list-style-type: none"> <li>- Inundation to provide flood pulse advantage</li> <li>- Rejuvenate backwater habitats for native fish</li> </ul>	
	Invertebrates	- unknown	

### 3.6.2 Factors not linked to high flows

A major concern with the application of prescribed high flows on a dammed river is that geomorphic high flow types are designed around the basis of achieving only specific sediment *transport* objectives. Rarely do they ensure the *supply* of sediment from upstream. Sediment supply and natural hydrological pathways have invariably been disrupted by human activities (especially when damming rivers), primarily in the period since European colonization in the western United States. Therefore, there is the potential that high flows for sediment transport applied without considering sediment supply issues will cause conflict and incompatibility with management objectives that require the preservation of a restricted supply of sediment. Kondolf and Wilcock (1996) highlight two such potential conflicts as:

- flows to flush fine sediments from gravel versus preventing gravel loss; and
- flows to prevent vegetation encroachment versus preventing gravel loss.

They suggest that other potential conflicts with high flow prescriptions include:

- floodplain building flows versus maintaining in-channel topographic diversity; and
- high flow prescriptions versus flood control / bank erosion constraints.

Overall, it is unlikely that high flow releases can fully counter flow and sediment process impairments in regulated rivers. Instead, they assist in reducing the impairments and are likely to require supplementary management actions (such as gravel augmentation and bank and channel reconstruction, etc.) to ensure that restoration objectives are met and are sustainable. Further, it is likely that competition between various management objectives in combination with practical and/or political restrictions on the magnitude of high flow releases will require that a compromised hydrograph (or series of hydrographs) be developed for prescription. Conjunctive actions may involve either, or both, sediment management and channel reconstruction actions alongside high flow prescriptions in order to aspire to the targeted success criteria. Where additional methods are required, a hierarchy of preferential actions may be conceived, based on the assumption that restoration of river processes is more desirable than restoration based on form alone. One such set of hierarchical preferences, presented by Downs et al. (2002), is:

- Non-structural techniques: improvements to hydrology and sediment transport processes through land use planning.
- Improving network connectivity: prescription of high flow pulses, removal of obstructions to flow (dams, weirs).
- In-stream measures for prompted recovery: small structures to bring about process-form improvements at the reach scale.
- Morphological reconstruction: suited primarily to low energy river systems where process-driven approaches cannot be invoked or may be very slow to act.

### 3.6.3 Steps 5A-5C: Analyzing high flows by type

The framework for high flow prescription illustrated in Figure 13 indicates the need for a variety of analytical methods to underpin the scientific application of high flow experiments. Critical steps involving the selection of analytical methods include:

- Step 5A – “choose key metrics & analytical method”, involving the identification of the key parameters of the threshold hydrologic/geomorphic objective, the understanding of the analytical assumptions, and choice of appropriate analytical methods to simulate project performance;
- Step 5B – “collect morphometric data; run simulation model/field tests”, involving collection of high quality baseline data to achieve a rigorous application of the appropriate analytical

method as the basis for specifying the combination of high flow magnitude and duration required for effective implementation;

- Step 5C – “sensitivity analysis; quantify uncertainty”, requiring, to the extent possible, a rationale treatment of the variability inherent to the estimates obtained from simulation modeling and the uncertainty associated with the model predictions;
- Step 7 – “choose key monitoring parameters” involving selection of parameters used to indicate an overall evaluation of the scheme (i.e., for evaluation monitoring after the high flow or series of high flows) and will likely involve the field parameters chosen earlier for identifying the critical thresholds in channel behavior. The latter are used to improve geomorphic system understanding and contribute to improved simulation models as the basis for completing the adaptive management process);
- Step 10 – “monitor response of key parameters”, requiring collection of field data during and after experimental high flows to test the analytical predictions, assess the overall impact of the peak flow, and thus to evaluate the conceptual models of system behavior.

For convenience, the analytical methods required are organized according to their associated high flow type to reduce the potential variety of high flow analyses into a manageable set. This section describes briefly the issues faced in analyzing each of the flow types and is centered on the information summarized in Table 4. *There is no generally accepted body of knowledge regarding either modeling or experimentation on which to base a summary of such analysis. In general, the magnitude and complexity of geomorphic change implied by each high flow type increases progressively through the table and, consequentially, the uncertainty associated with its analysis increases.* It is apparent that several classes of simulation model are required for analytical purposes. They range from well established one-dimensional hydraulic models used routinely in river engineering analysis and in which there is a often assumed a high degree of application confidence, through sediment transport models that provide predictions generally to an order of magnitude in confidence, to models developed recently by research scientists for channel morphology evolution (e.g., for river meandering) that have almost no application history and for which there can be little application confidence at this time. Potential field experiments for identifying critical thresholds in channel behavior during high flows are also described, as well as parameters for measuring overall project success. A summary of the state-of-the-science and input parameters for each of the simulation models, as understood by the project team, is provided in Section 3.7 and is intended to caution river managers interested in pursuing practical application of a particular model. A further overview, outlining the fundamentals of named field methods, is provided in Section 3.8 as an illustration for river managers of the techniques involved in each method.

Table 4. Analytical methods for assessing high flows.

Flow type	Hydrologic / geomorphic objectives	Key metric(s)	Key assumptions	Simulation model prospect	Field threshold monitoring methods	Post-project field evaluation data
<b><i>Depth maintenance flows</i></b>						
<b>In-channel flows</b>	Annual duration & timing of target flow magnitude	Flow depth		Hydraulic model	Stage-discharge monitoring	Hydrologic record
<b>Over-bank flows</b>	Frequency, duration & timing of over-bank flow magnitude	Over-bank flow depth		Hydraulic model	Stage-discharge monitoring	Hydrologic record/aerial photographs
<b><i>Channel bed maintenance flows</i></b>						
<b>Pool scouring flows</b>	Remove fine sediments from pool surface	Texture of pool surface	Sediment transport exceeds upstream supply of fine sediment	2-d hydraulic model, threshold of motion analysis	Suspended sediment transport monitoring upstream / in pools, scour chain in pool	Hydrologic record, pool surface texture analysis, measure of relative pool depth
<b>Riffle cleaning flows</b>	Net reduction in fine sediments in riffle matrix	Permeability (and/or grain size distribution) of bulk sample of riffle sediment	Sediment transport exceeds upstream supply of fine sediment	Bi-modal threshold of motion analysis	Sediment tracer analysis, permeability tests, bulk sediment texture analysis	Hydrologic record, permeability analysis, bed surface and bulk sediment texture analysis
<b>Riffle mobilization flows</b>	Mobilize coarse sediments to target depth with specified frequency	Gravel scour depth and/or largest grain size moved	Upstream gravel supply exists to replace gravel transported downstream	Threshold of motion analysis, sediment transport model	Bedload monitoring, tracer analysis, scour cores / chains	Hydrologic record, bed surface and bulk sediment texture analysis, facies mapping

Flow type	Hydrologic / geomorphic objectives	Key metric(s)	Key assumptions	Simulation model prospect	Field threshold monitoring methods	Post-project field evaluation data
<b><i>Channel morphology maintenance flows</i></b>						
<b>Margin accretion flows</b>	Encourage depositional processes on channel margins	Deposit stratigraphy and/or topography, age of vegetation	Upstream sediment supply exists	2-d hydraulic model, sediment transport model, sediment deposition analysis	Bedload/suspended load monitoring over bar, monitoring of bar sediment depth	Hydrologic record, repeat bar topographic surveys, stratigraphic analysis, dendrochronology, bar surface texture analysis
<b>Channel width maintenance flows</b>	Prevent channel narrowing	Channel width, age of bar and bank vegetation	Flows can overcome (scour/drown) marginal channel vegetation	2-d hydraulic model, threshold of motion analysis at channel margin	Bedload/suspended load monitoring, repeat cross-section surveys	Hydrologic record, repeat cross-section surveys, dendrochronology, aerial photographs
<b>Channel migration flows</b>	Allow active bank erosion and channel migration	Area reworked (rate of bank erosion and bar construction)	Upstream coarse sediment supply exists, flows competent to remove outer bank vegetation	Meander migration model/bank stability analysis	Discharge monitoring, bank erosion pins, repeat cross-section surveys	Hydrologic record, repeat planform surveys, aerial photographs,
<b><i>Floodplain maintenance flows</i></b>						
<b>Floodplain deposition flows</b>	Encourage over-bank sediment deposition	Deposition depth, spatial extent	Upstream sediment supply exists	Over-bank sediment dispersion model	Discharge monitoring, repeat floodplain topographic surveys, suspended sediment monitoring	Hydrologic record, repeat floodplain topographic surveys, aerial photographs, floodplain facies mapping
<b>Floodplain mobilization flows</b>	Encourage floodplain scour, initiate channel avulsions	Area of floodplain reworked (scour/new channel)	Flows can overcome (scour/drown) floodplain vegetation		Discharge monitoring, floodplain tracer analysis, scour cores/chains, repeat floodplain topographic surveys	Hydrologic record, repeat floodplain topographic surveys, aerial photography, floodplain facies mapping

### 3.6.3.1 Depth maintenance flows

We have identified two types of hydraulic flows, relating approximately to Reiser et al.'s (1989) "hydrologic event methods":

- flows that achieve a target in-channel flow depth; and
- flows that achieve a target over-bank flow depth.

Depth maintenance flows (Table 3) are defined by hydraulic rather than geomorphic parameters, and may be based on return period flow events.

#### In-channel flows

In-channel high flows are generally a sustained release of water in excess of the regulated baseflow with the objective of attracting fish during spawning season, promoting outmigration of juvenile fish, or suppressing predation by reducing river temperatures below the feeding threshold for predatory fish species. Predicting the release magnitude needed to achieve a minimum depth of flow requires use of a hydraulic model. Generally, a one-dimensional hydraulic model either for steady, uniform flow or for gradually varied flow (e.g., HEC-RAS) will be used. Such models depend heavily on the use of a hydraulic roughness coefficient for calibration (e.g., Manning's "n") but extensive use of such models, and the availability of hydrological records against which to calibrate and validate these models, means that they are generally reliable for average instream flow depth estimates at the reach scale. The biological advantage achieved by steady increases to instream flow can be assessed using the Physical HABitat SIMulation (PHABSIM) model (Bovee 1982) from the family of Instream Flow Incremental Methodologies, although the model is not suitable for assessing the impact of flood flows. This model will assess, under steady-state hydraulic conditions, the weighted usable area available to biota using empirically based "habitat preference curves" for specific species. Other models including those based on simulating reference reach conditions are available (e.g., RCHARC [Nestler et al. 1993, 1996]).

#### Over-bank flows

Over-bank flows are intended for cases in which the restoration objective is to provide the 'flood pulse advantage' (Bayley 1991) by allowing periodic floodplain inundation. This inundation allows rearing habitat to extend into secondary channels and floodplains, facilitating rapid rates of fish growth and increasing fish survival rates (Sommer et al. 2001). Both the in-channel and the over-bank flow types result in elevated flows that are not explicitly intended to cause channel morphological change (i.e., change is not part of the targeted flow objective) but, clearly, the prospect of channel change increases as the magnitude of the prescribed flow increases. Therefore, in practice, over-bank hydrologic flows may be the same flow with the same impact as the 'floodplain maintenance flows.' Overbank flows are subject to spatially-distributed roughness from the receiving floodplain and these effects are less well understood or calibrated. Hydraulic models for overbank flow estimates can use either a compound roughness estimate intended to be representative of the channel and inundated floodplain, or use multiple roughness estimates wherein the channel-floodplain is sub-divided into discrete sub-areas with homogeneous roughness prior to summing the individual flow estimates via one of several techniques used to improve the accuracy of the composite estimate (reviewed in Knight and Shiono 1996). Whereas instream flow depth estimates can probably be made without recourse to stage-discharge monitoring, such monitoring is probably advisable when prescribing flows to achieve a certain depth of floodplain inundation. Stage recorders can be deployed during peak flows and the local stage related to USGS hydrologic gauges with well-established rating curves. For hydraulic models based on Manning's "n", flow is inversely related to the roughness coefficient, so varying the coefficient will result in proportional changes in discharge. Similarly,

simulating an altered channel shape can also be used to gauge the changes in water depth estimates. Making inferences about habitat from one-dimensional hydraulic models introduces an array of potential additional error sources and, for PHABSIM, these are relatively well-documented (e.g., Mathur et al. 1985; Gore and Nestler 1988; Gan and McMahon 1990; Kondolf et al. 2000).

### 3.6.3.2 Channel bed maintenance flows

We have identified three types of channel bed maintenance flows. They are approximately equivalent to Reiser et al.'s (1989) "sediment transport mechanics methods":

- flows that scour fine sediments from pools;
- flows that remove surficial sand from riffles; and
- flows that mobilize gravel, to transport subsurface fines and reduce surface armoring.

Channel bed maintenance flows are likely to be preferred in cases where the primary restoration objective is to improve channel bed habitat without causing significant channel migration (however, see below). The distinction between the three channel bed maintenance flows is made for convenience in discussion rather than any proven threshold in reality. The first two flows are essentially intended to reduce fine sediment in the channel bed while leaving the coarser particles unmoved. The ability to achieve this, however, while existing in theory, is yet to be widely accepted. The third flow will mobilize coarser bed particles and thus may, in practice, be equivalent in magnitude to flows under the channel morphology maintenance category.

#### Pool scour flows

Pool scour flows are intended to scour silt, sand, and fine gravel deposited in pools to improve the quantity and quality of rearing habitat. There are no established methods to predict thresholds of sediment scour from pools. A major issue is that pool scour requires an approach that is sensitive to the topography of the pool. Therefore, sediment entrainment estimates based on one-dimensional hydraulics tied to simplified channel representations are inappropriate. Instead a two- or three-dimensional hydraulic model applied to a detailed terrain representation of the pool and upstream reach is required. The models can be used to predict a two-dimensional map of velocities for a particular flow (although subject to numerous uncertainties) (Wright 2001), and from this derive a spatially-distributed set of shear stress estimates. In combination with detailed knowledge of the grain size distribution on the pool bed, the estimates of bed shear could be used to predict the initiation of sediment movement as a proxy for indicating pool scour (Lane and Richards 1997). Recent advances in two- and three-dimensional modeling of flow velocities make this simulation a prospect (e.g., Lane et al. 1995, 1999; Swindale 2000), although not one that has not been tested in practice. Downs et al. (1999) and Wright et al. (2000) have obtained a reasonable correlation between shear stress calculated from a three-dimensional hydraulic model and bed morphological response in a fine grained channel with installed deflectors that may be a surrogate for using direct entrainment calculations. In all cases of estimated entrainment, there is a key assumption that extent of entrained material in the pool exceeds the amount of upstream-sourced sediment that is later deposited as the high flow recedes.

An alternative, field-based prospect is to track pool scour volumes using field methods based on monitoring the correlation between pool scour and discharge. The proportion of pool volume that is lost to infilling by fine sediment (i.e., the material intended for removal by pool scour flows) can be quantified by a  $V^*$  analysis, which estimates the fraction of pool volume filled with fine sediments (Hilton and Lisle 1993; Lisle and Hilton 1991, 1999) although the technique is more difficult to apply on large rivers. The applicability of the  $V^*$  measure to pool scouring flows needs testing. Analyses of  $V^*$  performance (Lisle and Hilton 1999) in multiple channels have

suggested the measure correlates well with fine sediment supply (in channels with abundant sandy sediment production), which suggests that the measure may be no more than an indication of relative sediment supply, rather than the ability of the flow to scour the pool. Conversely, Lisle and Hilton (1999) hypothesize that increasing the relative frequency of moderate high flows that selectively transport bed material such as surficial fine sediment may reduce the fine sediment volume in pools. Moderate high flows are contrasted with larger high flows that both entrain the armor layer (and thus release fine material stored at depth) and result in fine sediment delivery from contributing hillslopes in the watershed. On this basis, it will be necessary to test the  $V^*$  estimate during various flood events in order to gauge the most effective combination of magnitude and frequency, and the shape of the hydrograph of high flow events to achieve the desired effect. Alternatively, evaluation of the effectiveness of pool scouring flows in time can be achieved through repeat measurement of the pool grain size distribution along with repeat DTM surveys of the shape and size of the pool relative to the riffle elevation, tied to records of discharge.

### **Riffle cleaning flows**

Riffle cleaning flows are intended to mobilize surficial sand from riffles without significant mobilization of gravel. The primary goal of these flows is to improve the habitat for aquatic invertebrates and thus increase the food supply for native fish, without mobilizing gravel, which can be in short supply downstream of dams. Prospects for simulation modeling rest on being able to specify shear stress values that will mobilize sand without mobilizing gravel. Wilcock et al. (1996) argue that sand mobilization without significant gravel transport is possible because the transport behavior of the matrix sand differs from that of the framework gravel and cobble. There may be only a narrow window of flows, however, that achieve the objective of maximizing sand transport while minimizing gravel transport. This effect may be hard to achieve in practice because it will require a carefully controlled range of shear stresses with long flow durations and will thus require exacting accuracy both in the entrainment predictions and in the topographic representations of the riffle surface. We do not know of any existing analytical model designed specifically to predict rates of fine sediment removal from immobile gravel beds, although recent model developments by Wilcock (1997a, 1998) may hold promise in this regard. As with pool scouring flows, a key assumption is that mobilized fine sediments will be transported out of the reach of interest and will not be replaced by additional fine sediments transported into the reach from upstream and deposited in the riffle during the recession limb of the peak flow hydrograph. If the target flow successfully removes sand from riffles, one prospect is that the sand will begin to infill downstream pools and mechanical cleaning of pools may be required in parallel with the prescribed high flow (Wilcock et al. 1996).

The alternative to simulation modeling is to test for sand mobilization thresholds in discharges using field experiments such as sediment tracers to track sediment movement and surface and bulk samples taken before and after the high flow release. These field experiments would be done in conjunction with upstream monitoring of sediment transport to determine whether the mobilized sands are simply being replaced from upstream. Evaluation of riffle cleaning flows can be examined over the long-term by bulk sediment samples and surface facies mapping combined with permeability tests and knowledge of the hydrological record.

### **Riffle mobilization flows**

Riffle mobilization flows are intended to move both riffle gravels and interstitial fine sediment, ideally to a certain depth to ensure suitability for spawning habitat. The flow required to exceed the threshold of gravel motion or to exceed mobile armor can be estimated using a hydraulic model and a Shields shear stress analysis for sediment entrainment. We know of no sediment transport equation, however, that can estimate the scour depths, although changes in bed elevation

and surface grain size distributions can be estimated using certain sediment transport models (e.g., Parker 1990a, 1990b). The sediment transport model should be applied to a variety of locations to assess the variation in downstream flow requirements. In addition to the threshold of sediment transport, the quantity of sediment transport is also important. The quantity of sediment transport is a function of the duration and degree to which the transport threshold is exceeded. Depending on the ecological requirements and available sediment, the duration of the flow release can be varied to increase or decrease the amount of sediment transport. Models that examine sediment transport rates rather than only transport thresholds can be used to assess how the duration of the release affects the amount of gravel transported. As sediment transport models focus on average channel conditions, and are most accurate at higher sediment transport events, careful consideration should be given to ensuring that the answers sought of the model are compatible with its capability.

It is inherent to the assessment that the concern for gravel transport rates requires estimates of upstream gravel supply into the reach to ensure that the reach does not become supply limited over time. At one level, this may be achieved with sediment transport estimates through the upstream reach, but eventually concern will turn to the overall supply of gravel in the watershed. The prospect exists that if more sediment is being transported than is supplied to the channel (or stored in the bed), the riffle mobilizing flows could be detrimental to the stream system (e.g., reduced available spawning gravel areas). If the system is coarse sediment limited, then carefully planned gravel augmentation may need to be prescribed along with the riffle mobilizing flows to prevent existing spawning riffles from being scoured to bedrock or being left with sediment too coarse for salmonid spawning.

There are many potential uncertainties in sediment transport modeling. In particular, the values of the Shields coefficient (the coefficient that determines the critical dimensionless shear stress at which particles move) and the roughness coefficient are chosen rather than measured, and the estimate will depend heavily on an accurate assessment of the grain size distribution and topographic survey of the channel. Varying these parameters and examining the range of results can assist in assessing the potential error in the model.

The field alternative to simulation modeling is to monitor gravel entrainment thresholds and rates of gravel transport using tracer techniques and bedload samplers, respectively (reviewed in Sear et al. 2000). The depth of scour achieved under a particular flow can be examined using scour chains or cores (Lisle and Eads 1991; Harrelson et al. 1994). Upstream sediment transport monitoring can indicate the rate of transport versus upstream supply on an event-by-event basis, while repeated topographic survey of riffles can be used to indicate whether the riffle volume is increasing or decreasing in time relative to the flows received. Bulk samples and facies mapping could be used to indicate whether the particle size content of the riffle was changing in time.

### **3.6.3.3 Channel morphology maintenance flows**

Three types of flows that maintain channel morphology have been identified:

- flows sufficient to encourage depositional accretion at channel margins;
- flows that maintain channel width; and
- flows that promote channel migration (and which are linked to bar accretion).

Channel morphology maintenance flows are implicated in cases where the restoration objectives are linked intimately to the renewal of habitats associated with significant sediment transport, with bank erosion and pool formation, and with progressive change in the riparian patch dynamics. In practice the differentiation of flows may hard to achieve. They are separated here on

the basis that marginal accretion flows may be typical to sand-bedded channels, whereas width maintenance flows are a variation suitable for gravel-bedded rivers. Either flow may double as a channel migration flow but the distinction is made on the basis that the ecosystem objectives may be somewhat different under this flow.

Unlike channel bed mobilizing flows, where analysis and prediction can be based primarily on sediment movement potential indicated by sediment transport methods, thresholds in bar growth, bed morphology, and bank erosion require analysis capable of relating sediment movement to deposition, upstream supply, and channel geometry. Also, these features may be more cumulative rather than threshold phenomena. There are no established analytical procedures for predicting channel morphology, primarily because this requires two-dimensional analysis and thus has far more intensive data requirements than for one-dimensional analysis. It is essential, therefore, that experimental peak flows intended to alter or maintain channel morphology follow the adaptive management framework outlined in Figure 13 to maximize the potential to advance knowledge in this area and ensure that subsequent flows are optimized.

### **Marginal accretion flows**

The goal of these flows is to encourage deposition of (generally fine) sediment on channel margins. This could be necessary to improve conditions for the germination of riparian vegetation. Marginal accretion flows would generally be prescribed for streams that have little morphological diversity as a result of fine sediment depositing along the channel thalweg rather than along the channel margins. This condition is likely in channels where flows have been reduced to the extent that bankfull or overbank flows rarely occur and is exacerbated where there is the essential cessation of coarse sediment supply. Schmidt et al. (1999) demonstrate that, in the confined channels of the Grand Canyon, fine sediment deposited on the bed of the channel can be relatively quickly transferred to the channel margins during a large flood event, and that the extent of transfer was limited primarily by the flow magnitude. Where the goal is to move coarse sediment to replenish point or alternate bars in gravel-bedded channels, high flow events of considerably longer duration will be required. In this case the prescribed high flow is essentially equivalent to the channel migration high flow (see section below).

To overcome the problems inherent to averaging one-dimensional results in a real channel, prediction of marginal accretion flows ideally requires a two-dimensional model of boundary shear stresses in combination with an indication of the settling velocity of individual particles (Dietrich 1982). A simpler alternative is to ensure that the flows designed to cause marginal deposition are well above sediment transport thresholds for fine sediment, which can be assessed using the sediment transport models described for riffle mobilizing flows. It would then be assumed that marginal deposition will occur as a result of lateral sediment transfer during the high flow and as the flood recedes from the channel margins. Input required for the model and sensitivity tests would be the same as for riffle mobilizing flows. Similarly, the data required for analyzing accretion flows would be similar to riffle mobilizing flows but would also include aerial photography before and after the high flow event and detailed surveys of bar topography. Assessment of sediment supply to ensure that sufficient incoming sediment exists will be necessary, suggesting that the assessment technique will require a sediment budget analysis developed in parallel.

Evaluation of the longer-term effectiveness of bar accretion experiments could be achieved using repeat surveys of the bar in relation to flows received. This would document volumetric changes in conjunction with a combination of stratigraphic analysis, dendrochronology of vegetation burial (e.g., Hupp 1986), and surface texture analysis of the changing composition of the bank.

**Channel width maintenance flows**

Flow regulation results in a significant reduction in high flow events and the disruption of coarse sediment supply by the dam. Fine sediment transport may continue, however, if augmented by sediment obtained through channel entrenchment downstream of the dam and by sediment received from unregulated tributaries (e.g., Petts 1979). This sediment is deposited on the floodplain, at channels margins, and around tributary junctions causing the channel to narrow. The deposits are often conducive to vegetation establishment that causes the sediment deposits to stabilize and completes the channel narrowing process (e.g., Sherrard and Erskine 1991). Channel width maintenance flows are intended to prevent or reverse vegetation encroachment by scouring sediment and uprooting vegetation on the channel banks and bars. It seems probable that the flow required to uproot vegetation should be either of very high magnitude but of relatively short duration (to physically overcome the living mechanical strength of the roots) or consist of a long duration of inundation, to weaken the roots as the plant dies, followed by a moderately high magnitude flow to remove the plant. It is likely that flows to remove established vegetation are much higher than those required to remove young plants. The flows required to uproot vegetation will depend on the hydraulic roughness and root architecture of the species involved and the sedimentology of the channel margin, and the loading of flood debris on the upstream face of the tree (McBain and Trush 1997). Some research now exists that examines the rooting strength of common riparian tree species (mostly in relation to the bank protection prospects afforded by such species) (Simon and Collison 2002), but there are currently no available models that can predict the flow shear stress at which vegetation will be uprooted.

Mechanically, it may be reasonable to assume in coarse sediment channels that active bed load sediment transport will tend to destabilize vegetation rooted in the bar substrate, and that the shear stress at which vegetation rooted in channel banks will be scoured is equal to or greater than the threshold of motion shear stress for near-bank sediments. Therefore, modeling of both channel hydraulics and sediment transport will be useful for predicting the magnitude of channel width maintenance flows. Similar to the margin accretion flows, a two-dimensional account of boundary shear stresses is required, ideally, so that the sediment transport potential at the channel margins is understood. Again, a more realistic prospect may be simply to ensure that the flow safely exceeds that required for sediment transport of coarse sediment and hope that a combination of sediment transport and the drag forces on the submerged vegetation is sufficient to scour the bar and uproot the vegetation. Hydraulic models can also be used to ensure that there is sufficient flow depth above the vegetation of interest. Alternatively, for the Trinity River Flow Evaluation, riparian trees were mechanically felled by bulldozer following saturation of the riparian berm to obtain an indication of the critical moment of failure for the trees in conjunction with an understanding of the probable loading of the tree with large woody flood debris (McBain and Trush 1997). In these experiments, the drag coefficient of the tree was of relatively less importance than the dimension of the debris loading against the tree.

In the absence of modeling certainty, relationships between flow and removal of encroached vegetation may need to be empirically determined for individual streams, using an experimental approach. The approach is ideally suited to active adaptive management because a series of experiments will be required of different magnitudes and durations, and focused at different vegetation types in different topographic settings. Field experiments would complement laboratory and plot scale studies carried out elsewhere into rooting strength. Topographic surveys of pre- and post-experiment conditions could be used to indicate success in removing sediment. Overall evaluation of experimental success could be achieved by repeat channel width surveys in combination with aerial photographs and/or vegetation plot and transect surveys to document marginal vegetation changes (and possibly dendrochronology of living tree species to see if the overall age structure of the bank vegetation is altering in response to the experiments).

**Channel migration flows**

Channel migration flows are intended to achieve significant erosion of banks on the outside of bends and deposition on point bars, to restore floodplain construction by lateral channel migration. Johannesson and Parker (1989) suggested that channel migration is driven by the velocity perturbations along the outer channel bank. Similar to other channel morphology maintenance flows, channel migration flows reflect a combination of high discharges and upstream sediment supply. Various models of channel migration exist (reviewed in Howard 1996), although the model developed by Johannesson and Parker (1989) has been subject to the greatest application (Howard 1992; Larsen 1995; Sun et al. 2001; Larsen and Greco 2002). Prediction of the thresholds for initiating bank erosion is at the cutting edge of current research, so the bank erosion rate in the model is computed as a function of the difference between the near-bank shear stresses and the average boundary shear stress. It is possible that a threshold exists below which no channel migration will occur, and it is reasonable to assume that above the threshold, the higher the flow, the higher the rate of channel migration across a homogeneous floodplain. Models that predict channel migration use steady-state flow assumptions applied over long time periods and thus will not help in defining a flow release. Again, the default position may be to use sediment transport models to define a flow significantly in excess of that required to transport bed sediment and to assume that the process of bed load movement induces sufficient lateral velocity perturbations to initiate migration.

An empirical alternative to the application of a bank erosion model is to compare historical records of channel evolution to discharge records in order to reach an understanding of channel migration erosion thresholds and migration rates, especially in larger rivers with good historical coverage (e.g., the Sacramento River). Because migration models cannot define high flow magnitudes and durations, empirical observations of channel migration during high flows are vital in developing high flow prescriptions. Therefore, monitoring the impact of future flood events may provide a key to defining the necessary flows. In practical terms, it may also be necessary to remove bank protection before significant channel migration can occur.

Data required to empirically assess channel migration flows include longitudinal profiles, cross sections, estimates of hydraulic roughness, the grain size distribution of the channel bed and channel banks, maps or photographs of channel form, and historical records of channel planform and the hydrologic record. In addition, it is also important to understand bank properties such as the degree of cohesion, vegetation distribution, and root strength. The potential uncertainties in the sediment transport modeling are discussed in riffle mobilizing flows section, above.

**3.6.3.4 Floodplain maintenance flows**

Two types of floodplain maintenance flows are recognized:

- flows that transport fine sediment overbank; and
- flows that are capable of scouring overbank areas.

Again, these flows are separated on the basis of possible differences in restoration objectives rather than on proven differences in magnitude between the flows. In general the flows are required where objectives include a significant evolution in floodplain habitats through processes of floodplain deposition and erosion, although it is probable any single flow will have spatially-differentiated effects, causing erosion in some locations and deposition in others, along with channel migration.

Floodplains are created by lateral channel migration and overbank deposition (Leopold et al. 1964), and by braid bars in multi-threaded channels. Floodplain maintenance through lateral channel migration is considered under channel migration flows. Floodplain deposition flows will cause notable sediment deposition on the floodplain when the floodplain is inundated by water with significant concentrations of suspended sediments. Floodplain mobilizing flows (roughly equivalent to the ‘catastrophic stripping’ flows of Nanson and Croke 1992) are less frequent and require high energy flow across the floodplain to scour vegetation and expose underlying floodplain sediments in order to re-set floodplain vegetation communities. Both flow types are likely to increase floodplain topographic diversity.

### **Floodplain deposition flows**

Floodplain deposition flows are intended to provide fine sediments to floodplain soils as well as nutrients and water to support floodplain and riparian terrestrial ecosystem processes. Their two primary requirements are: (1) inundation of the floodplain; and (2) a supply of suspended sediment. The flow depth required for floodplain inundation can be predicted using hydraulic models suitable for floodplain application (see Section 3.7). Suspended sediment concentration is primarily a supply issue and can be assessed with empirical data calibrating the sediment load of overbank flows. In regulated rivers where reduced flows have caused large amounts of fine sediment to be stored in deep pools and along the channel thalweg, a high flow event may be able to scour the stored fine sediment and deposit it on the floodplain as an overbank extension of the marginal accretion flow.

Where there is sufficient fine sediment supply, the prime requirement for floodplain deposition is simply overbank flow, which can be evaluated with a hydraulic model as discussed earlier. The rate of floodplain deposition can be evaluated with a simple model that relies on field data calibration (e.g., Parker et al. 1996). Where greater detail is required regarding the deposition process, models have been developed that predict the diffusion of sediment away from the channel edge as a function of factors such as the sediment settling velocity, vertical sediment diffusivity, suspended sediment concentration, distance across the floodplain, and hydraulic gradient (e.g., James 1985; Pizzuto 1987). These models are in their infancy and will require detailed topographic information on the channel-floodplain system, in addition to bed grain size distributions and roughness estimates for both the channel and floodplain (reviewed in Marriott 1996).

The empirical alternative is to analyze in detail the morphology and processes existing with newly occurring overbank sediment deposition (e.g., Florsheim and Mount 2002) as an indicator of likely process rates and magnitudes. Floodplain deposition flows can be evaluated using a combination of periodic topographical surveys along with sediment facies mapping and aerial photography. Where model predictions have been made, they should be referenced to parameters such as floodplain inundation depths, suspended sediment concentrations, and sediment deposition thicknesses during and after the peak flow.

### **Floodplain mobilization flows**

Floodplain mobilization flows are intended to create areas of bare sediment on the floodplain floor in order to provide disturbance and initiate floodplain successional processes. Scour of vegetation, soil, and floodplain sediment requires high energy flows outside of the channel and is often associated with natural bend cutoffs, levee breaks, channel migration, and avulsion. There are no current analytical models that can be used to predict erosion of the floodplain. Conceptually, however, a two-dimensional analysis of overbank flows to indicate a flow depth sufficient to generate shear stresses to overcome the roughness offered by the floodplain sediment and vegetation would be required. Floodplain mobilizing processes may occur locally during

flows intended primarily for floodplain inundation or floodplain deposition. Important insights and useful data may thus be obtained from these lesser flows that could then be applied to estimating floodplain mobilizing flows.

Data required for empirical analysis include longitudinal profiles, topographic surveys, hydraulic roughness, maps or photographs of channel form, estimates of the role of riparian root strength on the floodplain sediments, and the hydrologic record.

In conclusion, it is reiterated that many of these flows are interrelated and that the ability to model the performance of several of the high flows ahead of application is extremely limited. This emphasizes the importance of field data collection and the use of high flow releases as experiments as well as management devices.

### **3.7 Analytical Models: Summary of State-of-the-Science**

This section provides a stand alone state-of-the-science overview of the analytical models named in the previous section, as reference in analyzing the various high flow releases to achieve the ecosystem objectives. It is not a comprehensive review of literature but more a guide to river managers potentially involved with high flow prescriptions. A thorough literature survey on the topic is probably warranted as part of developing high flow prescription capabilities, but is outside the realm of this project. Likewise, case study applications of the various models to specific high flow issues would require significant additional effort that is beyond the scope of this project.

Progress in the past half a century in hydraulics and sediment transport modeling is based on advances in sediment transport theories and computational technologies and facilities. Problems that might have been beyond the scope of modeling 20 years ago can now be answered relatively easily, and with relatively high confidence, with computer models. Hydraulic modeling capabilities are advanced beyond those of sediment transport. For example, one-dimensional hydraulic models can be developed and applied easily to evaluate water surface elevations in rivers, providing dependable results with minimal calibration. Two- or three-dimensional hydraulic models can also be applied with reasonable confidence if there are no resource restrictions on input data. Sediment transport models lag behind hydraulic models because their theory base is less well developed. The models are, therefore, essentially empirical and best used in coarse applications to predicting time- and reach-averaged conditions. Their calibration commitment is significant and the models are most accurate when the rate of sediment transport is high, allowing the considerable issue associated with the arrangement of bed particles to be minimized. Usable two- or three-dimensional sediment transport models exist only for suspended sediment applications in river estuaries. With these facts in mind, it is not difficult to understand that predictions combining sediment transport with channel morphology adjustment (e.g., meander migration models) are even less well developed. Overall, modeling of the effects of high flow prescriptions cannot be made with high confidence. In addition to extensive calibration requirements, consideration is required of the scale of the question posed against the scale of answer provided by the model, of the deterministic nature of modeling results against the seemingly stochastic nature of geomorphic changes and of the model accuracy in terms of whether correct predictions are true representations of environmental dynamics or result from a serendipitous canceling of opposing errors. Applications should be exercised with care and used in combination with field experimentation and the judgment of competent professionals. An overview of individual modeling scenarios is given below.

### 3.7.1 One-dimensional hydraulic analysis

One-dimensional hydraulic models, such as the U.S. Army Corp of Engineers' HEC-RAS gradually varied flow model, are highly reliable for predicting water surface profiles without requiring highly detailed channel topographic data. Such models are well grounded in fluid mechanics theory, requiring relatively simple calibration of the roughness parameter. Cross-section average values of velocity and shear stress are of limited value however in predicting local geomorphic responses to individual high flow events. The split-flow routines in one dimensional models are often used to simulate complex flow over floodplains, but cannot adequately capture the effect of flow divergence on floodplain sediment advection and scour. For these and other applications, two-dimensional models may be necessary.

### 3.7.2 Two- and three-dimensional analyses

Two-dimensional (e.g., RMA-2) and three-dimensional hydraulic models (typically site specific) are also well-based in hydraulic theory but are not used frequently due to their large input data and computational resource requirements. Generally, multi-dimensional models are most appropriate for analyzing short reaches, where the lateral and longitudinal length scales are similar. Recent advances in flexible grid algorithms and the growth in available computational power have allowed the spatial extent of analysis to be extended to longer reach segments in two dimensional modeling of in-channel (e.g., Miller 1998) and floodplain processes (e.g., Bates et al. 1997). Two-dimensional models are most appropriate for relatively high width-to-depth ratio channels and for floodplains, where vertical velocity components can be neglected. This approximation is not valid for simulating the interaction of flow with complex bed topography, such as in pools; in this case three-dimensional models may be required. The considerable investment in time and effort required for obtaining high resolution topographic data and preparing three-dimensional computations is probably only justified in a research context at the present time. In concluding a brief summary of the state-of-the-science in two- and three-dimensional model capabilities, Wright (2001) highlights the following uncertainties:

- 2-dimensional models: lack of effect of secondary currents, lack of mass conservation for finite elements methods, lack of grid independence, poor modeling of momentum transfer between main channel and floodplains, roughness specification, turbulence modeling;
- 3-dimensional models: roughness specification and wall function implementation, turbulence modeling handling of irregular geometries, boundary conditions at the inlet/outlet and free surface.

It seems probable that two- and three-dimensional models will continue to be used for specific applications but never fully replace one-dimensional models that are better suited to application over larger areas.

### 3.7.3 Instream habitat analysis

When considering specific habitat requirements it is necessary to restore 'natural' hydraulic habitats that are defined locally by the interaction of the flow with pool-riffle sequences, heterogeneity of the channel margins, planform sinuosity, and temporary aquatic habitats on the floodplain. Accordingly, habitat preference curves for different species of fish or different life stages can act as a method of target setting and are derived either from the literature, professional judgement, or from detailed field observations (Petts and Maddock 1994). Habitat preference curves are usually expressed as a suitability index from 1 (suitable) to 0 (unsuitable) for flow depth, velocity, and substrate. The most popular approach for simulating habitat preferences for different life stages and species of fish is via the Instream Flow Incremental Methodology (IFIM) and its underlying model, PHABSIM, (Bovee 1982), which computes the 'weighted usable area' (WUA) in a reach, usually as a function of the river velocity, depth, and substrate. River

discharge calculations are based on one of five hydraulic models chosen using available data and professional judgement. Numerous procedural, biological, and physical limiting assumptions prevent PHABSIM and IFIM from being wholly reliable (e.g., Mathur et al. 1985, Gore and Nestler 1988, Gan and McMahon 1990, and Kondolf et al. 2000). One of the strongest criticisms of specific sections has focused on the ecological interpretation of the WUA Index since it is commonly assumed that habitat (the WUA index) is a proxy for species biomass or abundance (Gordon et al. 1992). In response to these criticisms, a wide range of more complex approaches based on advanced understanding of the bioenergetics of fish biology, and more realistic representation and modelling of flow patterns are now at the research stage (Third International Symposium on Ecohydraulics 1999). The use of instream habitat models is restricted to the analysis of prolonged “average” conditions such as might be achieved with the release of a depth-maintenance flow as an enhanced baseflow condition (e.g. during spring snowmelt periods). They are not suitable for examining the impacts of individual flood flow events.

### **3.7.4 Sediment transport analysis**

#### **Entrainment**

The threshold of bed sediment motion has been extensively studied over the past century and the standard Shields non-dimensional shear stress threshold is widely used (Buffington and Montgomery 1997). Significant uncertainties remain however in predicting the spatial extent of bed mobilization due to variations in sediment embeddedness, the effects of complex bed topography, and the strong grain size dependence of sediment transport near the threshold of bed motion. Modeling of bed entrainment should be done in concert with bedload transport modeling because most bedload transport models have implicit or explicit assumptions about threshold conditions.

#### **Transport rate**

Numerous sediment transport models have been developed for predicting bedload, suspended load, and total load, all of which are either fully empirical (e.g., Parker 1990a, 1990b) or theory-based empiricisms (e.g., Bagnold 1986). The rate of sediment supply from upstream is the dominant control on suspended load, and thus total load as well, particularly for the fine sand, silt, and clay size fractions. Bedload models are most reliable in predicting transport rates at the reach average scale, and at present are poorly suited for two-dimensional applications due to the lack of understanding of lateral sediment transport processes. Without on-site calibration, the accuracy of bedload transport models is limited to roughly one order of magnitude. Calibration with bedload measurements is not a trivial exercise due to spatial and temporal variations in bedload size distribution and transport intensity and the effects of bedload samplers on transport dynamics. Models that explicitly treat individual grain size fractions (e.g., Parker 1990a or 1990b) are preferable, especially for simulating evolution of bed texture by selective transport at relatively low excess shear stresses.

### **3.7.5 Sediment dispersion analysis**

Sediment motion onto and across floodplains has been modeled as a purely diffusive process (e.g., Pizzuto 1987) and as a combination of advective and diffusive processes (e.g., Nicholas and Walling 1997). In either case, models must combine two dimensional predictions of water depths and velocities, with the time and spatial evolution of suspended grain size distribution and vertical concentration profile. Simulation accuracy is dependent on the quality of topographic data and also requires high spatial resolution calibration of hydraulic roughness. Model results will also be highly sensitive to the initial grain size distribution of sediments entering the floodplain from the main channel, so floodplain models need to be linked to models of in-channel

suspended sediment transport. Applied floodplain sediment dispersion modeling has become more feasible in recent years due to advances in high resolution low altitude laser swath mapping (e.g., Krabill et al. 1995) and the use of natural and anthropogenic sediment tracers (e.g., Dietrich et al. 1999). Accurate model predictions will, however, require extensive calibration using individual-event measurements of in-channel and overbank sediment concentrations and depths and grain size distributions of floodplain sediment deposits.

### **3.7.6 Bank stability analysis**

A number of models have been developed for predicting bank erosion thresholds, equilibrium channel width, and rates and patterns of width adjustment to changes in discharge and sediment regime (ASCE 1998). However, most models only apply to a narrow range of bank materials and hydraulic settings, and have generally not been independently tested in the field. Models for banks composed of non-cohesive sediments (e.g., Kovacs and Parker 1994) have been derived from sediment transport mechanics, while models for cohesive banks are typically based on stability analysis of planar slopes (e.g., Darby and Thorne 1996). The role of vegetation is the most poorly understood aspect of the problem (ASCE 1998). Models of cohesive and vegetated banks generally employ empirical erosion resistance coefficients that are model specific and can not be generalized. Although many field studies document relationships between site specific bank characteristics and bank stability (e.g., Simon and Collison 2001, 2002; Simon et al. 2000), no standard set of field measurements are available to characterize bank strength and erosion resistance. ASCE (1998) provide a comprehensive review of available models and propose a two stage procedure for selecting appropriate models for predicting equilibrium channel width and channel width adjustment. In 2001, the first version of a physically-based model for evaluating streambank stability including empirical coefficients for the effect of species bank top tree species was released by the USDA ([http://www.sedlab.olemiss.edu/cwp\\_unit/bank.html](http://www.sedlab.olemiss.edu/cwp_unit/bank.html)). This model does not yet incorporate research into the dynamic effect of changing water levels on the bank stability.

### **3.7.7 Meander migration analysis**

The leading model for predicting the rate and planform pattern of meandering channel migration is by Johannesson and Parker (1989), which forms the basis for the applied meander migration models of Larson (1995) and Howard (1992). The model linearizes the governing equations for flow through curved channels, and captures the dynamic coupling between the flow field, bedload sediment transport, and bed topography. Bank resistance to erosion is represented by an empirical coefficient that can be calibrated using maps or photographs documenting past channel position and knowledge of bankfull depth and channel slope. The model is sensitive to initial and upstream boundary conditions and is not easily adapted to disturbed channels where channel planform morphology reflects the pre-disturbance discharge and sediment supply regime. An application of the model under specific circumstances is presented in Larsen and Greco (2002).

## **3.8 Field Methods: Techniques Summary**

This section provides a stand alone summary of the field techniques implicated in the analysis of high flows in Section 3.6. The brief descriptions are intended as an introductory reference for field managers and are not related to specific case studies in high flow prescription. Field methods include:

- aerial photographic analysis,
- channel cross sections,
- topographic survey,
- longitudinal profile,

- facies mapping,
- field estimation of roughness factor,
- pebble counts,
- permeability,
- $V^*$ ,
- bulk samples,
- freeze cores,
- scour chains,
- scour cores,
- tracer rocks,
- bank erosion pins,
- bank strength,
- floodplain sediment traps,
- vegetation survey,
- suspended sediment sampling,
- bedload sediment sampling, and
- stream gauges.

### 3.8.1 Aerial photographic analysis

Aerial photographs from different years can be compared to assess the amount of channel change over time (Figure 23). Wide scale aerial photography coverage began in the 1930s and continues to date. Sequential aerial photographs can be used to identify (Kondolf and Larson 1995):

- changes in land use;
- direct alterations to the channel, such as channelization, levee construction, bank protection, other flood control structures, or reservoir construction;
- major sources of coarse and fine sediment from clear cuts, landslides, forest fires, road construction or failure, residential development, agricultural development, or intensive grazing;
- channel migration;
- riparian encroachment;
- sediment storage sites such as reservoirs, debris jams, and channel constrictions; and
- reaches with features that effect flow and sediment transport, such as bedrock controls, and steep or confined bedrock channels.

When using aerial photography to make channel form comparisons, a table should be constructed that lists the date and discharge from a gauging station that can be compared for all sets of the aerial photographs, as aerial photographs taken of the same channel in the same year can appear very different depending on the flow in the channel. Additionally, the annual maximum discharge over the period of record should be consulted to link channel features to high flow events (Kondolf and Larson 1995). In addition to qualitative descriptions of channel change, orthorectified aerial photographs can be used to make quantitative measurements of channel migration in planform or changes in riparian vegetation.

### 3.8.2 Channel cross sections

A channel cross section is a profile of the channel bed and flood plain surveyed perpendicular to the center line of the channel using either an auto level, total station, hand level, or a rod and tape stretched across the channel (Figure 24). Cross sections taken before and after high flow events can show changes in channel form, such as scour, deposition, or channel migration. Surveying channel cross sections is relatively straightforward; however, certain guidelines should be

followed including the list below, which was compiled from Kondolf and Micheli (1995) and Harrelson et al. (1994):

- Cross section end points should be permanently monumented. Typically monuments include rebar driven into the subsurface, a cap placed in cement, a pin driven into a tree, a cap drilled and cemented into a boulder, or marks chiseled into boulders or cement.
- Cross section end points should be referenced to a permanent features (benchmarks) at the site, such as, buildings, bridges, trees, fence lines, or large boulders on a site sketch map with distances and azimuths from the end points to the permanent features or located on aerial photographs (Figure 25).
- Photos should be taken of the cross section from both banks and looking upstream and downstream to aid location of the cross section. Additionally, the cross section end points and benchmarks should be photographed as vegetation growth or other site changes can obscure monuments within a few months.
- Cross sections should be located in representative reaches of the stream and should be located away from obstructions that could alter the channel form, such as, large boulders, large woody debris, breaks in slope, or bedrock outcrops.
- For a study reach, 10–15 cross sections should be taken on repeating morphological units including riffles, pools, runs and the apex of meander bends.
- Cross sections should include channel features such as:
  - Slope breaks
  - Water surface (WSE)
  - Terraces
  - Left bank (LB)
  - Right bank (RB)
  - Left edge water (LEW)
  - Right edge water (REW)
  - Thalweg (TLG)
  - Bankfull indicators (BKF)
  - Bed material
- Elevations should be taken at regularly spaced intervals and at breaks in slope and a minimum of ten elevations should be taken for each cross section.

### 3.8.3 Topographic survey of bars

In addition to cross section surveyed with an auto level, a topographic map of bars can be created with a total station. Repeat topographic surveys of bar surfaces can be used to quantify the volume of sediment deposited or scoured from the bar. The same basic procedures used for cross sections should be followed for surveying using a total station. The survey should be tied into a permanent benchmark and a site sketch made to show prominent features, locations of benchmarks, and locations of the total station. Survey points should conform to a grid pattern that is fine enough to capture breaks in slope and deposition or scour of material.

### 3.8.4 Longitudinal profiles

Longitudinal profiles (long profiles) provide information on the slope of the channel bed, the energy slope of the surveyed discharge, and the energy slope of historical or previous high flows if high flow indicators can be identified in the field (Figure 26). Generally, a long profile is an elevation profile of the channel thalweg. The elevation of the thalweg (the deepest part of the channel), the channel banks, terraces, high water marks, morphological unit, and stationing should be recorded. As with surveying cross sections, the start and end points of the long profile should be properly documented so that the profile can be repeated. As a rule, the minimum distance of the long profile should be at least 20 channel widths. The morphological units should

be recorded with elevations. When the slope is calculated from the long profile the start and end points for the distance and elevation should be from similar morphological units. For example, the channel slope should be calculated from the distance and elevation change from the head of a riffle at the top of the long profile to the head of a riffle at the end of the long profile. Although direct comparisons between long profiles can be difficult because of inaccurate stationing, general observations about pool filling or riffle elongation can be made to gauge the effects of high flows.

### 3.8.5 Facies mapping

Facies maps show the location and extent of homogenous bed material units in streams (Figure 27). Facies maps can be of coarse detail covering many reaches where only major changes in bed material are mapped, such as cobble, gravel, sand, and silt. More commonly, facies maps cover a single reach and map significant changes in the bed material. These maps capture hydraulic sorting on point bars and fining above and below riffles. These maps are limited to the surface layer, but they can be useful in quantifying the change that a channel undergoes before and after a high flow event. Facies maps can capture the scouring of fine sediment from riffles and the deposition of sand and fine sediment in distinct patches.

### 3.8.6 Field estimation of roughness factor

Hydraulic models used to predict the stage in a channel for a given flow require that the modeler input a value for the roughness of the channel. Several methods have been developed, of which the most common method used in the United States to calculate discharge is the Manning's equation:

$$Q = \frac{1.49}{n} AR^{2/3} S^{1/2}$$

where  $Q$  = discharge (cfs),  $n$  = Manning's  $n$ ,  $A$  = cross sectional area of the wetted channel (feet<sup>2</sup>),  $R$  = hydraulic radius (feet), and  $S$  = slope (Dunne and Leopold 1978). Manning's  $n$  can either be estimated from published tables of single  $n$  values for different channel types, by comparing the study reach to books with photographs of channels with different  $n$  values, or by field estimating individual components of  $n$ .

Photographic guidance for  $n$  is provided in Barnes (1967) and Hicks and Mason (1991), who calculated Manning's  $n$  for numerous rivers associated photographs of each reach with their appropriate roughness coefficient. Barnes (1967) covers the United States, while Hicks and Mason (1991) covers New Zealand. The similarity of climates between California and New Zealand makes the Hicks and Mason (1991) applicable to rivers in California. The study reach in question can be compared to the photographs in the books and a roughness coefficient can be estimated (Figure 28).

Composite estimates of  $n$  follow a procedure developed by Cowan (1956 cited in Chow 1959) (Figure 29). Under this procedure,  $n$  is calculated as:

$$n = (n_0 + n_1 + n_2 + n_3 + n_4) m_5$$

where  $n$  = Manning's  $n$ ,  $n_0$  = a value for channel alignment,  $n_1$  = a value for channel material,  $n_2$  = a value for variation in the channel cross section shape and size,  $n_3$  = a value for obstructions in

the channel,  $n_4$  = a value for vegetation in the channel, and  $m_5$  = a value for channel alignment (Chow 1959).

### 3.8.7 Pebble counts

The Wolman (1954) pebble count is the most widely used and standardized method to determine the surficial size distribution of material on the bed of a stream. The size distribution of the sampled patch of gravel can be calculated after measuring the intermediate axis (b axis) of 100 pebbles (Figure 30). High flows have the potential to scour particles from riffles, deposit fine sediment on top of riffles, or mobilize the streambed. Pebble counts can be measured before and after high flow events to assess changes in the size distribution associated with scour and deposition of the streambed. The method requires isolating a homogenous patch of gravel that is representative of the riffle and sampling 100 pebbles. If there are numerous patches of gravels of different size classes, a site map should be made of the different patches and a pebble count should be performed at each patch. Pebbles can be collected either from a grid that has been marked with flagging or randomly by selecting pebbles from a homogenous patch. The sampler must close or avert their eyes from the channel bed to prevent a natural bias of sampling the largest pebbles on the bed. After the intermediate axis of 100 pebbles is recorded, a size class frequency can be calculated and the results plotted. Pebble counts are often used in place of bulk sampling because they can be performed quickly in the field. Additionally, an adequate sample for a bulk sample in a coarse riverbed can often exceed 500 pounds.

### 3.8.8 Permeability

Barnard and McBain (1994) developed a method to measure intergravel permeability using a modified Terhune Mark VI permeability standpipe (Figure 31). Permeability measurements can be used to predict salmon embryo survival using gravel quality indexes. Fine sediment can infiltrate into spawning gravel and reduce the intergravel flow and dissolved oxygen that salmon embryos need to survive. A permeability standpipe can be used to measure intergravel flow before and after high flows to see if the high flow releases accomplished the stated objectives, such as mobilizing the bed of a riffle and flushing fine sediment from the gravel to improve intergravel permeability. To measure permeability:

- a permeability standpipe is driven into the stream bed to a depth of 0.8 to 1.0 feet;
- a battery powered vacuum pump is used to extract water from the permeability standpipe with a 1 inch pressure head into a calibrated container;
- the volume of water extracted and the time of extraction are recorded;
- the water temperature is recorded; and
- permeability and embryo survival rates are calculated from the field measurements.

Fifteen samples within each riffle are recommended because of high inter-riffle variability. Additionally, five replicates at each sample location should be taken.

### 3.8.9 Bulk samples

Bulk sampling is another method for sampling the surface and subsurface of a channel. Material is removed from the channel and sieved to determine the size class distribution. Numerous methods have been developed to excavate the material, but the most common one is associated with the McNeil sampler and the many modifications of the original design (Figure 32). The sampler is worked into the channel bed and the encased sediment is removed by hand and deposited in a reservoir. McNeil-type samplers consist of a hollow tub that ranges in diameter depending on the size of the surface material. For spawning sized gravels the tub diameter generally ranges from six to 12 inches. The hollow tub is attached to a larger tub that acts as a reservoir for the sediment that is removed. The depth of sediment that should be removed

depends on the scientific objective of the sampling. For example, analysis related to the quality of riffles for spawning habitat, the sampler will often require insertion of at least one foot into the channel bed. Once the appropriate depth is reached, a plug is inserted to the bottom of the sampler to capture the fine sediment that is in suspension. Samples can be transferred to containers and sieved at a lab or onsite (Platts et al. 1983). Church et al. (1987) proposed a criterion to determine the minimum sample size that is based on the largest clast in the sample. The criterion states that the largest clast in the sample up to 32 mm should comprise no more than 0.1 percent by weight of the total sample. For samples that include clasts between 32 mm and 128 mm the criterion is relaxed to one percent. Using this criterion, samples taken from riffles suitable for Chinook salmon spawning ranged in weight from 330 to 770 lbs.

An alternative method of bulk sampling is provided by freeze cores. A hollow probe is driven into the bed of the channel and a cryogenic fluid (typically liquid nitrogen or carbon dioxide) is poured into the pipe, freezing the interstitial water in the gravel surrounding the pipe (Figure 33). The pipe is then removed from the streambed with the surrounding gravel frozen to the pipe. The bed material is collected for sieving and the surface material can be separated from the subsurface layer at this time. The freeze core was designed to sample a vertical section of the channel bed and avoid mixing of bed material during extraction that occurs in other bulk sampling methods (e.g., McNeil Sampler). Everest et al. (1980 as cited in Platts et al. 1983) developed a procedure for sampling the vertical stratification of freeze cores. Additionally, freeze cores capture the stratification of benthic organisms which are frozen along with the sample (Gordon et al. 1992). Freeze cores can be taken before and after high flows to quantify the change in the size distribution of bed material. Freeze cores may alter the undisturbed bed by driving the freeze pipe into the channel bed. Secondly, the sample from a freeze core is small and there are typically large variations between samples adjacent to each other. In comparison to bulk samples, freeze core samples are suspected of overestimating the coarseness of the bed due to the irregular boundary around the pipe that preferentially samples larger pebbles (Lisle and Eads 1991), although the converse situation has been known (Kondolf, pers comm.).

### 3.8.10 Fine sediment pool filling

In gravel bedded streams that are characterized by pool riffle sequences, the  $V^*$  method (Hilton and Lisle 1993) can be used to quantify the amount of fine sediment that is transported during high flows.  $V^*$  is a measure of the fraction of total pool volume that is filled with fine sediment. Measurements of  $V^*$  before and after high flows can quantify the amount of fine sediment that is winnowed from riffles and other areas in the channel where the boundary shear stress is high and deposited into pools where the boundary shear stress is lower during the receding limb (Lisle and Hilton 1991). To calculate  $V^*$ , the volume of a pool is determined at low flow (the residual pool) by taking measurements at five to eight transects. The water depth and depth of fines in the pool is measured at 30 to 60 locations. The residual pool is defined by the coarse substrate that lines the pool to the crest of the riffle below the pool (Figure 34). To measure the depth of fines a metal rod is pushed into the substrate of the pool until an armored layer is encountered and the depth of the fine sediment deposit is noted (Lisle and Hilton 1991).  $V^*$  has been used to assess pool filling in numerous basins in southern Oregon and northern California (Lisle and Hilton 1999).

### 3.8.11 Scour chains

Scour chains can be used to measure the amount of scour or deposition from high flows, by burying a chain in the channel bed (Figure 35), along a surveyed cross section. One end of the chain is buried below the depth of maximum projected scour and the other end is laid on the bed surface. The length of exposed chain is measured and the elevation of the exposed chain is surveyed. Depending on the width of the stream, five to ten scour chains should be buried at each

cross section. Lisle and Eads (1991) recommend burying scour chains at two to five cross sections at each study site. After high flows the cross sections should be re-surveyed and the length of exposed chain measured. If deposition has occurred, the chain can be carefully excavated and kinks or bends in the chain indicate scour followed by deposition (Harrelson et al. 1994).

### **3.8.12 Scour cores**

Scour cores are similar to scour chains except that they consist of a column of painted rocks. Pits are excavated along a cross section of channel and backfilled with painted clasts of a representative size class or the  $D_{50}$  or  $D_{84}$ . The elevation of the top clast in the column is surveyed. After high flows, the cross section is resurveyed to see if any of the painted clasts were transported downstream or buried by sediment. If the channel has been downcut, the painted clasts should be located downstream and the distance from the scour core recorded, as well as, the intermediate axis of the clast. If the cross section experienced deposition, the scour cores should be excavated to the first clast to determine the amount of deposition.

### **3.8.13 Tracers**

Tracers are clasts of various sizes that are placed along a cross section or in patches in a channel. After a high flow the clasts are relocated and the sizes that moved during the high flow and the distance that they traveled is recorded. There are numerous methods to mark and retrieve clasts, but the most common method is to paint clasts in florescent colors so that they can be easily relocated after transport (Figure 36). Because clast can be either buried in place or after transport, other techniques that have been developed (Sear et al. 2000) to increase the retrieval of traces, including:

- nuclear tagging,
- magnetically tagged clasts,
- aluminum particles,
- acoustic tracking,
- radio tracking, and
- magnetic detection.

Tracers can be used to validate models that predict thresholds of bed mobilization. However, particle movement is dependent on turbulence, and the density, shape, and size and compaction of the surrounding material as well as shear stress (Gordon et al. 1992).

### **3.8.14 Bank erosion pins**

Stream bank erosion can be measured by driving pins horizontally into the stream bank leaving an exposed portion to be re-measured after high flows (Figure 37). The end of the exposed pin should be surveyed to a benchmark and after each measurement of the exposed portion; the pin should be re-set into the bank to the original degree of exposure. Suggested lengths for pins range from 3 feet to 9 feet and the diameter should be at least 1/16 inch (Goudie 1981 cited in Gordon et al. 1992). Problems associated with bank erosion pins include local scour around the exposed portion of the pin and debris catching on the exposed portion of the pin that increases the local scour or pulls the pin from the bank (Gordon et al. 1992). A recent advance in pin technology is the development of the Photo-Electronic Erosion Pin (Lawler 1992) that allows for continuous bank erosion monitoring so that bank failures can be more accurately associated with flow discharge.

### **3.8.15 Bank strength**

Bank strength can be qualitatively assessed by visual observation of the banks. Important factors to consider include, parent material, looseness of the material, armoring of the bank by vegetation, development of root structures that hold the bank together, the amount and location of loose material from recent deposition or available for mobilization during high flows, and the slope of bank. Additionally, the investigator can look for evidence of recent bank failure or scour. Stream bank strength should be assessed during low flow when the majority of the bank is visible to the observer. In cohesive banks, quantitative measurements of bank strength can be examined by measurements of the pore-water pressure at different depths in the bank, using tensiometers.

### **3.8.16 Floodplain sediment traps**

Floodplain sediment traps collect fine sediment that is deposited during high flows. Typically, numerous patches of artificial grass of a known area are staked to the floodplain surface and, after high flow events, their accumulated sediment is removed for analysis. Whatever artificial surface is used the surface roughness should be similar to that of the surrounding floodplain.

### **3.8.17 Vegetation survey**

One commonly used method for determining the composition of riparian vegetation is measuring cross sections perpendicular to riparian complexes (Figure 38). Typically, at least five cross sections are established at each study site and the end points are permanently marked with stakes. The endpoints should extend far enough into the non-riparian zone to capture potential growth of the riparian zone in future surveys. The species of plants encountered along the transect should be recorded on a set interval and the community type composition is calculated by tallying the total number of species collected by species in relation to the total number of interval in the transect. The cross section should be documented with photographs at the channel edge and at the end stakes. After high flows survey transects should be revisited to quantify the change in riparian vegetation.

### **3.8.18 Suspended sediment sampling**

The total load (the material that is being transported) of a stream is comprised of the suspended load and the bedload. Suspended sediment samplers collect finer particles that are transported in suspension. The standard sampler is the US DH-48, which is a depth integrated sampler (Figure 39). The sampler is designed to collect a sample continuously as the sampler is raised and lowered into the stream and the nozzle is designed so that the velocity at the nozzle is equal to the stream velocity. The sampler is lowered into the stream at discrete locations across a cross section. The individual samples from each vertical are combined and the sediment in the sample is weighted (Gordon et al. 1992).

### **3.8.19 Bedload sediment sampling**

Bedload refers to the sediment that a river transports by rolling, bouncing, or skipping along the bed. It is difficult to obtain accurate bedload transport rates from hand-held samplers as the bedload transport is highly variable in time and space. Most bedload is transported in bursts that can significantly alter the amount of sediment captured during the sample period. Additionally, peak transport occurs during floods or high flow events which make sampling difficult (Edwards and Glysson 1998). Hubbell (1964 as cited in Gordon et al. 1992) identifies four types of bedload samplers that have been developed:

- pit sampler,
- basket sampler,
- pan samplers, and

- pressure-difference samplers.

The Helley-Smith pressure difference bedload sampler is the most commonly used and is available in different sizes to sample large and small streams (Figure 40). Bedload sampling using the Helley-Smith sampler should be taken along a previously surveyed cross section. Numerous samples should be taken across the channel depending on the width and the irregularity of the channel bed. A site for sampling should be chosen that does not have any sediment trapping features upstream of the sampling location. When possible, the sampled cross section should be located on stable material to prevent biased results as the sampler will often dig itself into the surface of the bed. Velocity, length of sampling period, and stage should be noted. The sample can be sieved and weighed to develop a sediment transport rating curve from samples taken at different flows (Edwards and Glysson 1998).

### **3.8.20 Stream gauging**

Most major streams in California have gauges that are maintained by either the USGS or the California Department of Water Resources. Additionally, many water utilities, flood control agencies, and irrigation districts maintain their own gauges (Kondolf and Larson 1995). USGS data is easily downloaded from the internet, while gauge data from other sources may not be as easy to obtain. In some cases, the actual discharge in the reach of interest may require investigation of the canal network for the river, inputs from tributaries, or water diversions. Potentially, a gauge could be located above an irrigation diversion canal. To calculate the discharge for a study reach below the diversion, the diverted discharge must be subtracted from the upstream river gauge. If the stream under investigation is not gauged a similar watershed that is gauged could be used with a correction for different watershed areas. The second option is to install a staff gauge or pressure transducer. The advantage of a pressure transducer is that it can be left in the field to continuously log data for an extended period of time, while the staff gauge must be observed. For both methods the gauge needs to be properly located. A gauge should be located in a straight reach that is free of channel obstructions that could cause backwater effects. A stable reach should be selected, where the cross section will remain as stable as possible. When installing gauges, the USGS often pours a sill of concrete to create a uniform cross section. Once a cross section is established, data for a stage discharge rating curve can be calculated. The discharge is determined by calculating the area of the wetted channel and multiplying by the velocity of the channel at a given stage. The area is calculated by plotting the water surface elevation, read off of a staff gauge, on the surveyed cross section. The velocity is measured by dividing the channel into verticals and using a current meter to link stage to discharge.

## 4 SELECTION OF THREE STREAMS FOR PILOT STUDY

One component of this project is to select three streams for pilot study according to the prospect that their river ecosystem processes can be restored. The streams were to encompass one large dammed river, a small dammed river and a small river regulated by abstraction interests but no large dam. The selection rationale builds on previous deliberations of CALFED described in the Pilot Watershed Acquisition Program (PWAP) Stream Selection Recommendations (CALFED 2002) and the CALFED ERP Independent Science Board memorandum (Kimmerer et al. 2002).

*Note: the selection rationale described here is based on the likelihood of restoring physical processes, and does not consider the practicalities or likelihood of being able to obtain water from willing sellers. It is, therefore, supplemental and complementary to the process of stream selection being undertaken as part of the EWP planning process.*

### 4.1 Selection Rationale

The PWAP selected streams were based on USFWS recommendations of 12 streams with the highest priority for flow augmentation, based on the following primary factors:

- streams recommended for instream acquisitions during Stage 1 of the Ecosystem Restoration Program Plan Strategic Plan for Ecosystem Restoration;
- size of investment in the watershed by the Anadromous Fish Restoration Program and CALFED;
- number of anadromous salmonid species identified for recovery in the CALFED Multi-Species Conservation Strategy present in each stream; and
- USFWS ranking of biological priority.

The following were secondary considerations:

- availability of quantified flow objectives to facilitate recovery of anadromous salmonids;
- availability of biological monitoring data; and
- existence of active local groups focused on watershed restoration.

The PWAP recommendations resulted in the 12 streams being narrowed to a first tier of the five most appropriate streams, namely Butte Creek, Clear Creek, Deer Creek, Mill Creek and the Tuolumne River.

Concerns regarding the relegation of scientific concerns to secondary importance in the PWAP method led to the CALFED ERP Independent Sciences Board developing an alternative listing of criteria designed to prioritize those streams where flow releases may be sufficient to reactivate geomorphic processes (the Board having decided that reactivating geomorphic processes was the most desirable form of high flow prescription) (Kimmerer et al. 2002). The Board's principal prioritization criteria were:

1. flow ratio (i.e., the proportion by which flow could be augmented),
2. availability of monitoring data,
3. ongoing research and restoration,
4. institutional support expected from other programs,
5. extensibility of results to other streams and situations,
6. experimental tractability,
7. presence of species of concern,
8. breadth of scope,
9. expected degree of impact if successful, and

10. absence of a hatchery, which could confound investigations.

Using the PWAP recommendations as provisional guidance, participants in the Science Board's Adaptive Management Workshop Flow Regime Forum selected Clear Creek and the Tuolumne River as the most promising locations for large-scale flow experimentation, with Butte Creek, Deer Creek and Mill Creek serving as potential sites for short-term water acquisitions to support smaller-scale flow manipulation experiments. The relative merits of Clear Creek and the Tuolumne River are summarized in Table 5.

**Table 5. Advantages and disadvantages of geomorphic-scale flow enhancements in Clear Creek and the Tuolumne River.**

Site	Advantages	Disadvantages
Both	Active restoration Chosen by CALFED public process Can design channel to fit flow Some monitoring Will capture people's attention No hatchery	Power costs No coordinated monitoring program Salmonid stocks of uncertain origin
Clear Creek	Smaller (easier to deal with, measure) Clear (fish are visible for study) Bureau of Rec. gets to recapture the water Population response detectable Restoration closer to historic conditions Decision analysis model available	Smaller (less important to overall restoration) Engineering needed to control flow Not very representative of Central Valley streams Potential mercury in available gravel
Tuolumne River	Bigger (important to San Joaquin salmon) Good escapement time series Strong relationship of escapement to flow implies strong flow response Results more applicable to other CV streams Two salmon models	Bigger (harder to deal with, measure) Water is opaque at high flow Gravel pits in lower river Mercury a potential issue

Source: Kimmerer et al. (2002)

As described in previous chapters, the scientific questions implicit in defining linkages between flows and fluvial geomorphic processes will require conducting flow experiments. Consequently, the selection of Clear Creek and the Tuolumne River as the most promising locations for conducting flow experiments, as determined by participants of the Adaptive Management Workshop, make a strong argument for selecting Clear Creek and the Tuolumne River as two of the pilot streams to test the methods described in this report. Both Clear Creek and the Tuolumne River also match the selection criteria delineated for this project:

- suitability of the streams for fully testing the methodology (e.g., rivers for which a majority of ecological processes are relevant will have higher priority, and those that allow testing for different morphodynamic types);
- the availability of previously collected data in readily accessible form; and
- the likelihood that riverine ecological processes can be restored.

The rationale adopted in this study builds upon the previous work of the USFWS and the CALFED Adaptive Management Workshop. Readily available data was assembled from the five rivers previously identified by the USFWS WAP prioritization process as the first tier of high flow restoration prospects. Available documentation included:

- Deer Creek Watershed Conservancy. 1998. Deer Creek watershed management plan. Prepared for the Resources Agency, State of California, California State Water Resources Control Board, and the U.S. Fish and Wildlife Service.
- McBain and Trush. 2000. Habitat restoration plan for the lower Tuolumne River. Prepared for Tuolumne River Technical Advisory Committee (Don Pedro Project, FERC License No. 2299). McBain and Trush, Arcata, California.
- Western Shasta RCD. 1996. Lower Clear Creek watershed analysis. Prepared for the Bureau of Land Management, Western Shasta RCD.
- Williams, J.G., G. M. Kondolf, and E. Ginney. 2002. Geomorphic assessment of Butte Creek, Butte County, California. Prepared for Chico State University Research Foundation with funding from U.S. Fish and Wildlife Service, Davis, California.
- CALFED. 2002. Executive summary of the Pilot Watershed Acquisition Program's stream selection recommendations. CALFED, Sacramento, California.

Information from these documents was used to construct Table 6, summarizing the criteria of concern. It is apparent that the previous considerations of Clear Creek and the Tuolumne River that both are regarded as highly suitable test sites, and they have the benefit of providing the variety of river type and probable flow prescription type to make them very useful test sites. In addition, of the remaining three creeks, Butte Creek has the advantage of a recent geomorphic baseline report summarizing conditions in the creek and is the preferred choice.

**Table 6. Selection criteria applied to Central Valley tributaries identified in the USFWS first tier for high flow restoration potential.**

River	Morphodynamic Types	Potential High Flow Test Type	Disturbance	Ecological Process Potential	Available Data	Potential for Restoration
Butte Creek	Confined bedrock channel, confined gravel bed, unconfined gravel bed	Centered on winter high flows	Gold mining, levee construction, bank stabilization measures, urban encroachment, hydro dams, irrigation diversions	High anadromous species ranking	Biological monitoring data available & quantified flow objectives Geomorphic assessment 2002.	ERPP flow acquisition recommended
Clear Creek	Confined bedrock, confined gravel bed, unconfined gravel bed	Centered on spring flows, opportunities for winter flow	Irrigation diversions, major storage dam, vegetation encroachment, gravel mining, gold mining, migration barriers	Medium anadromous species ranking Good population response detectable (what does this mean?)	Biological monitoring data available & quantified flow objectives	Restoration closer to historic conditions (what does this mean?) ERPP flow acquisition recommended
Deer Creek	Bedrock, gravel bed	Centered on winter high flows	Cattle grazing, logging, bank stabilization	High anadromous species ranking	Biological monitoring data available	ERPP flow acquisition recommended
Mill Creek	Not determined	Centered on winter high flows	Not given	High anadromous species ranking	Biological monitoring data available	ERPP flow acquisition recommended
Tuolumne River	Large unconfined gravel bed; sand-bed	Centered on spring flows	Large storage dam, gravel mining, gold dredging	Medium anadromous species ranking Strong flow response detected	Biological monitoring data available & quantified flow objectives	ERPP flow acquisition recommended

## **4.2 Description of Potential Pilot Streams**

### **4.2.1 Butte Creek**

Butte Creek drains 147 square miles of the northern Sierra Nevada and southern Cascade mountains before joining the Sacramento River near the Sutter Buttes. Elevation in the watershed ranges from 7,000 feet in the headwaters to 200 feet at Chico. From Chico, Butte Creek flows across its alluvial fan to the Butte Basin and joins the Sacramento through either the Sutter Bypass or Butte Slough. Land use in the upper watershed is dominated by timber and hydropower production. Butte Creek is flanked by residential development from the foothills to the City of Chico. Below Chico agriculture is the dominant land use. Regulation from hydropower dams on Butte Creek is minimal, but diversions can leave the channel with little flow during the summer irrigation season. Butte Creek supports spring-run Chinook salmon and steelhead, which are both listed as threatened under both California and federal Endangered Species Acts (Williams et al. 2002).

### **4.2.2 Clear Creek**

Clear Creek drains 238 square miles of the Trinity Mountains and is the first major tributary to the Sacramento River below Shasta Dam. Elevations in the watershed range from 6,000 feet in the headwaters to 400 feet at the confluence with the Sacramento; however, the majority of the watershed is below the 4,000 feet snowline. Clear Creek has been subject to aggregate mining and is regulated by Whiskeytown Dam (approximately RM 17), which is part of the Central Valley Project and was built in 1963. Clear Creek supports fall run chinook salmon (Western Shasta RCD 1996).

### **4.2.3 Tuolumne River**

The Tuolumne River is the largest tributary to the San Joaquin River and originates over 11,000 feet in the Sierra Nevada. The Tuolumne drains 1,900 square miles and joins the San Joaquin River near the city of Modesto. Land use ranges from grazing and aggregate mining in the reach below La Grange Dam to the City of Waterford. Below Waterford agriculture is the dominant land use. The Tuolumne is regulated by Don Pedro Dam, which was built in 1970 and has a storage capacity of 2.03 million-acre feet. Two major irrigation diversion canals are located at La Grange Dam (RM 52.2), which is down stream of Don Pedro Dam (McBain and Trush 2000).

## 5 DRAFT SCIENTIFIC HYPOTHESES

The material below has been developed in response to the need for testable hypotheses for high-flow experimentation under the EWP Pilot Water Acquisition Program. The hypotheses are examples developed from discussions held under CALFED's Adaptive Management Forum. They do not represent an exhaustive list and have been developed primarily with the Tuolumne River in mind. It is the nature of the hypotheses that they will need to be modified to suit the specific morphodynamic functions and disturbance characteristics of the host river whenever applications are contemplated. For some of the examples, a brief overview is provided of concerns central to developing an experimental design.

The hypotheses developed below involve two issues related to high flow prescription, namely:

- sediment transport and instream habitat; and
- salmonid growth in gravel-bedded stream: in-channel versus floodplain.

Other key questions for which high flow experiments could be developed include:

- spatial separation of warm-water predators and salmon smolts;
- suspended sediment transport;
- attraction flows;
- riparian tree regeneration;
- channel migration / riparian forest structure; and
- summer base flows / native fish species composition.

### 5.1 Sediment Transport and Instream Habitat

#### 5.1.1 Problem statement

Can we design a scaled-down channel and floodplain, gravel augmentation regimen, and flood hydrographs that will achieve the following geomorphic objectives?

- mobilize the channel bed every 1–3 years;
- maintain designed planform morphology (especially channel width) over the long term (e.g., after large floods), avoiding net aggradation and degradation;
- maintain a targeted framework gravel size distribution on bars (e.g., in the size range preferred by salmonids); and
- remove fine sediments from gravels.

These are a selection of possible geomorphic and biological considerations associated with a scaled channel, gravel augmentation regimen, and flood hydrographs (e.g., riparian regeneration) that could be the subject of separate adaptive management experiments.

#### 5.1.2 Summary of existing information

There has been considerable interest in the prospect for maintaining habitat quality under conditions of regulated flow, centering on issues related to sediment transport and morphological change. Rather than attempt a cursory summary here, refer to Section 3 for details related to many of the concerns raised by this issue.

#### 5.1.3 Overview of experiment

A series of progressively larger experimental flow releases will be used to determine the relationship between flow and the geomorphic experiments discussed below. Intensive

monitoring and evaluation of channel conditions will be required both before and after each high flow in order to target the individual hypotheses. For purposes of geomorphic evaluation, the ability to test hypotheses and to make meaningful conclusions about geomorphic processes will improve directly as a function of the number and differing magnitude of high flow releases.

#### **5.1.4 Hypotheses and experimental designs**

##### **Bed mobilization**

It is desirable for habitat purposes that, even under regulated regimes of flow and sediment transport, the channel bed is mobilized at least once every 1–3 years. For flow prescription purposes it is critical that our sediment transport models accurately predict the flow that will mobilize a given grain size distribution on the bed.

*Hypothesis:* Sediment transport models can predict accurately the discharge that will mobilize the bed of a given grain size distribution.

*Experimental design:* The first step is to define what we mean by “bed” and “mobilize”. The channel bed involves surfaces from the deepest part of the channel to the highest surface on a point bar. We will deal with this problem by monitoring at several points on a cross section which will allow, potentially, the derivation of more than one relationship between flow and bed mobilization. Mobilization can likewise have several definitions, such as incipient motion of the D50 or D84 or motion of the entire surface layer moving, and may involve some minimum depth of scour. Therefore, it is necessary to investigate movement of a variety of particle sizes (e.g., D16 to D96) using tracer particles, scour chains and cores distributed across several cross sections representing different bar/pool features (e.g., in a meander bend from the pool up to the top of a point bar and in a relatively straight trapezoidal reach). After each progressively higher pulse flow, we will document for each position on the cross sections which size particles moved and, to the extent practicable, how far they moved. Experimental results will be compared to the predictions of sediment transport models, and implications drawn concerning their effectiveness relative to limitations imposed by the one-dimensional nature of practicable models.

##### **Channel planform**

In river systems regulated by large dams, it may be necessary to design and construct a channel and floodplain morphology that is appropriate to the reduced flows and sediment transport experienced by the channel in order to maintain a valued diversity of habitat. This happens because the channel morphology existing prior to the dam has been effectively “paralyzed” since flow regulation. Providing prescribed high flows within the paralyzed channel will result only in the slow reduction in channel capacity for the foreseeable future. Constructing a new channel and floodplain morphology provides a means of dramatically reducing the time required for the channel to reach a new dynamic equilibrium form. In the new channel, prescribed high flows will provide the means of effectively stimulating meander processes that provide the basis for the continued diversity and evolution of channel and floodplain habitats. Designing and constructing a sustainable channel and floodplain morphology so that no net change occurs in the channel width or in bed elevation requires an understanding of the reach sediment budget under current conditions and those following the introduction of the prescribed high flows to ensure that systematic instability (long-term aggradation or degradation) does not occur.

*Hypothesis:* It is possible to design and construct a channel and floodplain morphology that will tend towards a dynamic equilibrium and persist over the long term in a regulated river.

*Experimental design:* the experiment involves two factors: the first is to understand the reach sediment budget in relation to reaches upstream and downstream in order to design a channel that does not tend to systematically depart from its design intentions. The second is to understand the implications for the sediment budget of prescribing high flows to invoke geomorphic processes within the channel. The experiment should aim at the accurate calibration of a magnitude-frequency calculation of sediment transport processes under the prevailing (regulated) flow regime and under a new regime of intended prescribed flows. Advances in computing capability mean that it is computationally permissible to develop flow frequency curves based on 15-minute flow intervals records (or the shortest possible time step available) to reduce the systematic underestimation of sediment transport potential caused by averaging flows over longer time steps (particularly in smaller, flashier rivers). A thorough analysis and step-by-step method for magnitude-frequency analysis are provided in Soar (2000). Assuming reasonably accurate flow gauging information, and control for, or incorporation of, any non-stationarity inherent to the data set, the primary experimental component is to obtain accurate calibration of the sediment rating curve for design reach, and reaches upstream and downstream of the design reach. This will require either calibrating the sediment transport model against sediment transport records for a number of high flow events, or developing a high quality sediment rating curve directly from the monitoring results. The most effective, but expensive form of monitoring is to construct continuously-recording bed loads traps so that sediment transport volumes can be associated directly with the contributing discharge.

### **Framework gravel size distribution**

Framework gravel size distributions are maintained by regular occasions of sediment transport combined with an upstream supply of appropriately-sized material to replace the material lost downstream through transport processes. In regulated rivers the frequency and duration of sediment supply and transport are disrupted. Commonly, sediment transport occurs with less frequency, duration and intensity (i.e., with smaller, shorter-lasting “high flows”) and the supply of coarse sediment to the river will be totally disconnected downstream to the first unregulated tributary capable of delivering coarse sediment to the mainstem river. Maintenance of a targeted gravel sizes distribution requires a sediment transport model capable of predicting the depth and grain size transported under different flow scenarios in combination with an understanding of the dynamics of upstream sediment supply.

*Hypothesis:* It is possible to predict a framework gravel size distribution that will be maintained in the long-term under the conditions of altered sediment transport and supply commonly found downstream of dams.

*Experimental design:* The experimental high flow studies required are similar to those described in Wilcock (1997b) focusing on the entrainment, displacement and transport of sediment tracers. While the total volume of sediment transport is of importance in understanding the permanence of framework gravels (relative to upstream supply), changing gravel quality through time may be defined by the frequency at which individual grains are entrained and the length of single displacements (the distance traveled). Wilcock (1997b) proposes inserting tracer gravels into the bed as marked particles using a large cylinder to facilitate the sub-division of a large sample, vertically sub-sampled if necessary. Transport characteristics are examined after high flow events by examining the remaining tracers and tracking the moved particles.

### **Fine sediment removal from gravels**

In regulated rivers, flows capable of sediment transport are often restricted to those capable of transporting only fine sediment particles. Over time, deposition of these fine particles in gravel beds leads to infilling of interstices between the gravels, with deleterious impacts for salmon

habitat. High flows are required capable of transporting these fine sediments from the framework of coarser particles. However, this transport must occur without significant transport of the coarser particles because upstream gravel supply to the reach is quite probably limited due to the impact of the dam. Success in this endeavor requires a sediment transport model capable of predicting the magnitude, duration and frequency of flows required to transport fine sediment without also transporting coarser particles.

*Hypothesis:* In a regulated river, it is possible to maintain a gravel bedded channel without a progressive increase on the quantity of interstitial fine sediment.

*Experimental design:* High flow experiments are required to provide field evidence for the existence of local shear stresses capable of winnowing sand from riffle gravels without significant mobilization of the gravel. This will require a sediment transport model capable of predicting selective entrainment, as a basis (e.g., Parker 1990), and detailed estimates of local near-bed velocity at the location at which sand transport is being monitored. For experimental purposes, these estimates may be obtained as part of a two or three dimensional hydraulic model if such a model can be calibrated accurately in the near-bed zone. Monitoring of sand transport could be based on repeat grain-size analysis of a representative sample of the gravel-sand sediment mix, or by suspended sediment monitoring/bed load monitoring if an experiment could be designed to trap only locally-derived sediment. Given the practical difficulties with the latter approach, the former is considered to be the most feasible.

## **5.2 Salmonid Growth in Gravel-bedded Streams: In-channel vs. Floodplain**

### **5.2.1 Problem statement**

Can a scaled-down channel be designed that allows for floodplain rearing and increased growth of juvenile salmonid at discharges that are lower than would be required to inundate existing (relict) floodplain surfaces?

### **5.2.2 Summary of existing information**

Survival of outmigrating Central Valley fall-run juvenile salmon smolts in the spring is thought to be greater for larger fish and those undergoing earlier outmigration. There is convincing evidence from the Yolo Bypass (Sommer et al. 2001) and the Cosumnes River (P. Moyle, pers. comm., 2002) that juvenile salmonids grow faster on the floodplains than in nearby reaches of the main river channel. This is thought to be due to warmer temperatures and higher levels of invertebrate prey, primarily chironomid larvae and pupae, in the floodplain. The chironomids become abundant within a few days of floodplain inundation. It is not known why the chironomids become available so quickly. A likely explanation is that the chironomid taxa present have a life history strategy of colonizing seasonal wetlands with larvae and pupae estivating during the dry periods.

Both the Yolo Bypass and the reach of the Cosumnes River that has been studied represent habitats typical of Central Valley rivers near the Delta (e.g., they have very low gradients, large floodplains, and sand-bedded main channels). Sand-bedded channels typically have low invertebrate production except on submerged large woody debris (Benke et al. 1985). Main-channel rearing of juvenile salmonids in sand-bedded reaches would therefore be expected to result in relatively low salmonid growth rates, explaining in part why faster growth would occur on the inundated floodplain of these rivers. The steeper gravel-bedded reaches of the Central

Valley would have higher in-channel benthic invertebrate production than sand-bedded reaches. It is not known to what extent floodplain rearing in gravel-bedded reaches would result in a substantial growth advantage over the main channel. In addition, many gravel bedded reaches have terraces near the river and therefore have relatively narrow floodplains. The effect of floodplain morphology on fish growth is not known (e.g., in narrow floodplains, greater water exchange with the river may limit the warming of floodplain waters, thereby affecting both invertebrate production and juvenile salmonid growth rates).

### **5.2.3 Overview of experiments**

This set of experiments is intended to evaluate whether a restoration strategy that includes floodplain rearing in the gravel-bedded reaches will result in faster growth than that observed when rearing is restricted only to the main channel. Enclosures containing individually marked fish will be installed in both main channel and adjacent inundated floodplain sites in experiments designed to document growth rates under various conditions.

### **5.2.4 Hypotheses and experimental designs**

#### **Floodplain water temperatures**

Fall-run salmon typically spawn in the San Joaquin River system from October through December, with the majority of the spawning occurring in November. Fry emergence often starts in January and peaks in February. Cold water temperatures in late winter and early spring can limit growth rates regardless of food supply. Water temperatures on the floodplain may be warmer than in the main channel because the water is shallower and has a greater residence time (i.e., is more easily warmed by insolation).

*Hypothesis:* Water temperatures in late winter and early spring will be warmer on the floodplain than in the main channel.

*Experimental design:* Continuous recording thermographs will be placed on transects perpendicular to the channel to assess the effect of proximity to the main flow of the river on warming. Additional thermographs will be placed to represent different hydraulic conditions that may affect warming (e.g., in backwaters on the floodplain that have greater water residence time than in the rest of the floodplain). Thermographs will also be placed in the adjacent main channel. Meteorological conditions, especially cloud cover, air temperature, and wind speed will be recorded in order to evaluate potential relationships with the daily temperature patterns on the floodplains. If water temperatures are warmer on the floodplain, bioenergetic modeling will be used to assess the effects of warmer temperature on growth rates.

#### **Chironomid life history**

There are important management and ecological implications if the abundance of chironomids on the floodplain is due to chironomid life history traits that allow seasonal wetlands to be exploited for rapid juvenile development during the wet season while allowing immature individuals to survive until the next wet period by estivating during the dry periods. For example, if floodplains are not inundated with sufficient frequency or duration, the chironomids may not be able to become established in large numbers. Since the food of juvenile salmon rearing on the Cosumnes floodplain and Yolo Bypass consists predominately of chironomids, it appears that a critical element of a floodplain growth strategy will be to provide favorable conditions for chironomid taxa that use floodplain habitats.

*Hypothesis:* The frequency and duration of floodplain inundation and floodplain substrate composition will affect the abundance and/or species composition of chironomids on the floodplain.

*Experimental design:* Floodplain reaches with known inundation histories will be mapped. Floodplain inundation pattern (frequency and duration) and substrate composition will be used to stratify the floodplain. Estivating chironomids will be sampled from the different strata during the dry season. Aquatic chironomids will also be sampled during the wet season. The abundance, species composition and stranding crop biomass of chironomids from the different strata will be used to develop a model of floodplain chironomid ecological requirements.

### **Floodplain food availability**

For floodplain rearing to result in faster growth than in the main channel, temperatures must be warmer, or food supply greater, or both. Differences in invertebrate prey numbers, total biomass, species composition, and size distribution will affect the relative bioenergetic advantage of the channel and the floodplain for rearing juvenile salmon, and will allow determination of the individual effects of food supply and temperature on any differences in growth observed in the floodplain versus the main channel.

*Hypothesis:* The availability and quality of the invertebrate prey base is greater in the seasonally inundated floodplain than in the main channel.

### **Juvenile salmon growth rates**

Documentation of differences in growth rates of individually marked fish known to rear exclusively on the floodplain or in the main channel would be the best evidence for the likely success of providing for a floodplain rearing strategy as part of designing a scaled-down channel.

Growth rates in the same environment may vary with the size of the salmon fry. Smaller fry may grow faster (as a proportion of body weight) than large fish if the prey base consists of small invertebrates (such as chironomids). The growth advantage of the floodplain may therefore be more pronounced for small fry than for larger fish, which can exploit the larger invertebrates that may be available in the main channel. Because smaller fry for fall-run salmon are most abundant in the late winter/early spring, which is when cold water temperatures are most likely to be limiting growth, this would suggest that January–March would be the time period when floodplain inundation would be most likely to benefit rearing juvenile salmon.

*Hypothesis:* Juvenile salmon growth rates are higher on the floodplain than in the main channel, particularly for smaller fry.

### **Floodplain habitats utilized by rearing salmon**

In order to provide suitable floodplain rearing conditions, it is important to know what water depths, vegetation structure, and velocity rearing salmon will use.

In particular, it is important to determine what depths are suitable, because this will greatly affect required water volumes. While newly emergent fry prefer shallow stream margins, larger juvenile salmon typically utilize deeper water. Water depths of 20 cm or greater greatly diminish the effectiveness of avian predators such as egrets and herons. Vegetation such as grasses or sedges may cause juvenile salmon to utilize shallower habitats than they would otherwise, in part because the overhead cover reduces predation risk from avian or terrestrial predators such as raccoons. High water velocity on the floodplain (especially during managed releases) is unlikely to preclude rearing, except in limited areas such as near the main channel or in back channels.

*Hypothesis:* Water depth and velocity, in combination with vegetation structure, can largely explain the distribution and abundance of juvenile salmon on the floodplain.

### **Piscine predation**

If the water on inundated floodplains is warmer than in the main channel this might encourage warm water fish to also move on to the floodplain and begin preying on juvenile salmon earlier in the season than might otherwise occur. In contrast to predation by avian predators, predation by piscine predators may be limited or precluded by shallow water. Emergent vegetation, such as sedges or reeds, can greatly reduce the foraging efficiency of predators such as black bass. Determining the conditions that minimize predation would greatly help in channel design (especially with regard to desired floodplain vegetation) and establishing target flow depths.

*Hypothesis:* Juvenile salmon on the floodplain are better able to avoid piscine predation with more complex vegetational architecture and/or with shallower depths.

### **Stranding**

In natural systems, the decrease in discharge on the receding limb of the hydrograph is relatively slow, and fish rearing on the floodplain can make their way back to the main channel as the floodplain becomes dewatered. When discharge in regulated streams is decreased too rapidly, juvenile salmon can be stranded, particularly in relatively flat areas such as floodplains, where large areas are dewatered with a relatively small decrease in flow.

*Hypothesis:* The rate of stranding of juvenile salmon in floodplain habitats is a function of rate of change of discharge and stage, and the topographic complexity of the floodplain.

## 6 CONCLUSION AND PROSPECT

Prescribing high flow releases in regulated rivers offers the prospect of partially off-setting the environmental impacts of flow storage and water abstractions and allowing some rehabilitation of downstream channel habitats. Geomorphic understanding and high flow experiments to date lead us to recognize two fundamental conditions necessary for successful action. The first is that high flow releases require a commitment to long-term planning and to repeated releases of varied magnitude, duration, and timing—single releases are inadequate. The second is that high flow releases in highly degraded rivers are unlikely to succeed without supplementary management actions designed to off-set the continued lack of sediment supply and the fact that released flows are unlikely to match pre-regulation flood discharges. Supplementary actions may include periodic gravel augmentation and morphological reconstruction of the channel perimeter.

The primary purpose of this document has been to review the physical scientific basis against which high flows can be analyzed to determine if we can confidently predict their effects. The general summary of our review is that we have insufficient real-world examples of high flow releases to provide a reliable basis in experiential understanding, insufficient empirical data regarding sediment transport under high flow conditions to be knowledgeable about the interactions between flow and the channel perimeter under specific conditions, and insufficient modeling expertise to provide an assured level of confidence in their predictions. However, the current state of understanding does enable us to outline ‘pathways’ towards the predictive capability we desire. We have examined these pathways using a classification of high flow types to sub-divide prospective impacts. It is clear that improved scientific understanding and predictive ability is critically dependent on well-planned, executed, and evaluated high flow release experiments, in addition to generic advances in scientific understanding obtained from on-going geomorphic research. In particular, advances in mathematical models and model calibration and validation are especially important to provide the feasibility-level testing that will be required prior to obtaining funding for high-flow releases.

Next steps in this process include: investment in high-flow release experiments; collection of detailed field data obtained under high-flow conditions; evaluation of high-flow field data contextualized by watershed history to maximize its transferability; and development of predictive models. These steps require a balance between improvements in understanding as the basis for planning in general and analyses formulated for specific watersheds. It may be appropriate to expand pathways developed in this report to include hypothetical situations conditioned by morphodynamic river type (e.g., for sand- and gravel-bedded rivers subjected to certain disturbance regimes) and for specific target objectives (e.g., to return lateral channel activity, fish spawning habitat, etc.). There is also a need to develop example-led plans targeted to reaches in particular watersheds; this is the focus of future steps in CALFED’s Environmental Water Program.

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